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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

FIFTEENTH ANNUAL MEETING
APRIL 26, 27, 28, 1934
WASHINGTON, D. C.
AND
BERKELEY, CALIFORNIA
JUNE 20, 21, 1934

PART I

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JUNE, 1934

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now seven sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, and (g) Hydrology. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section; the Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology.

Annual assemblies of the Union and annual meetings of its sections for the discussion of reports and for symposia are held each year. The first thirteen assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C.; in 1933 and 1934, in addition to the annual general assemblies and meetings of each of the seven sections held in Washington, D. C., meetings of the Section of Hydrology were held at Berkeley, California. The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1929, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, and fourteenth annual meetings were published in June 1931, June 1932, and June 1933, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, also one of the miscellaneous publications of the Council, includes the transactions of the fifteenth annual meetings held at Washington and at Berkeley. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The fifteenth annual assembly of the Union and the meetings of all its sections at Washington, D. C., were held April 26, 27, and 28, 1934, in the building of the National Academy of Sciences and National Research Council. The western meeting of the Section of Hydrology was held June 20 and 21, 1934, in Berkeley, California, where the University of California generously provided a meeting-place.

The reports and papers presented at the fifteenth general assembly were concerned largely with progress in development of the United States Weather Service in line with the recent recommendations of the Science Advisory Board in relation to studies of movements of major air-masses and the use of aerological observations in weather-forecasting. Included also were a number of reports on the upper-air data obtained during the International Polar Year of 1932-33. As a matter of record, a short report on the Fifth General Assembly of the International Union of Geodesy and Geophysics has been added in the Transactions upon request of the Executive Committee.

Several papers presented to the Section of Geodesy related to geodetic and gravimetric work in Canada, Mexico, and the United States. Other papers were devoted to the determination of longitude as a part of the international program of 1933, to instrumental developments, and to the effect of Moon's position on observed clock-corrections.

The Section of Seismology heard progress-reports from the United States Coast and Geodetic Survey and the Jesuit Seismological Association, on installations of tiltmeters, and on first-order leveling as an aid in seismological research. Several papers reported on the earthquake of September 6, 1933, and its bearing on the problem of the deep earthquake, on weathering correction, on values for dilatational wave-velocities, and on quarry-blasting. A paper by our Mexican colleague, Dr. Sánchez, told of the relation of the Bay of Acapulco to earthquakes in southern Mexico.

Several papers submitted to the Section of Meteorology reported on the reorganization of ocean weather-records for new applications and of climatological, aerological, and river-gage data made possible by the Civil Works Administration and Public Works funds. Mountain meteorology and its history were covered in several important contributions. Sounding-balloon work and aerological studies of the International Polar-Year program were reported. Other papers dealt with the surface of subsidence, atmospheric ionization near the ground during thunder-storms, and lightning-discharges.

In the Section of Terrestrial Magnetism and Electricity, Dr. Schonland of South Africa spoke on the study of atmospheric electricity there. Several papers were given on atmospheric-electric and auroral and earth-current observations of the International Polar Year in Alaska and Canada. Señor Sandoval reported on magnetic secular-variation and Captain Heck reviewed problems of magnetic surveys. One paper dealt with the effect of magnetic activity upon secular variation. Three papers were concerned with cosmic radiation and with ozone-measures. In the radio field four papers were presented on atmospherics, on radio-transmission studies in geophysical investigations, on the aid of radio in geological mapping, and on relation of radio with earth-potential observations. Dr. Kaplan presented an account of the production of the auroral spectrum in the laboratory. Progress-reports of nine organizations were received and a brief report of the Lisbon meeting of the International Association was made.

Progress-reports were made to the Section of Oceanography for the Hydrographic Office, the International Ice Patrol, the Coast and Geodetic Survey, and regarding work in the Russian Arctic, while the Committee on Oceanographic Activities in North America covered the work of other institutions on the Pacific and Atlantic sides of Canada and the United States. Two papers dealt with surface-temperatures and with temperature-salinity correlation.

In the Section of Volcanology a fine series of papers was concerned with the rare chemical constituents, the thermal decomposition of some carbonate minerals, geyser-basins, volcanic dust in relation to climate, the rôle of volatiles in titanium deposits, the year's volcanic activity, the viscosity of magmas, and basaltic flows.

The Section of Hydrology held three sessions in Washington and several sessions in Berkeley. The annual reports of the nine permanent committees on research as presented at Washington are published in these Transactions. Twenty-eight papers at Washington and fourteen papers with discussions at Berkeley evidence the wide interest in hydrological research and its economic importance. In conjunction with the meetings in Berkeley there was held also the annual meeting of the Western Interstate Snow-Survey Conference.

In view of the many contributions from the Section of Hydrology and from the Snow-Survey Conference, and to facilitate wider distribution, these Transactions are published and bound in two parts. Part 1 includes proceedings of the fifteenth general assembly and those of the sections of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, and Volcanology at Washington, while Part 2 is devoted to proceedings of the Section of Hydrology at Washington and at Berkeley including those of the Snow-Survey Conference. [The expense of publishing the many reports and papers in Part 2 has been provided largely from funds contributed through the initiative of the Special Finance Committee of the Section of Hydrology.]

Geophysicists from Canada and Mexico took active part in the meetings of 1934, submitting progress-reports of governmental activities and of results of geophysical researches stimulated by their national committees. The Meteorological Service of Canada was officially represented by Messrs. J. Patterson, B. W. Currie, and E. H. Vestine.

The General Secretary's task of revising and editing the manuscripts was shared through preliminary editing by the secretaries of section. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, contributions solicited by a special committee of the Section of Hydrology including a substantial one from the National Academy of Sciences, and contributions from members of the Union, from the Harvard University, and from the Carnegie Institution of Washington. C. C. Ennis read and corrected the entire typed copy while each author, except for a few who could not reply in time, also revised his matter as prepared for publication. The final manuscript for planographic reproduction was prepared by J. J. Capello as in former years, and to him is due in large measure the promptness of publication so well executed by the Kirby Lithographic Company of Washington. The General Secretary is indebted to W. C. Hendrix for reproducing many drawings--the originals submitted not being suited for planographic reproduction--to J. W. Green for photographic work, and to W. E. Scott for typing some tables.

The Executive Committee of the Union thanks the speakers, guests, and members taking part at Washington and at Berkeley. The present Transactions illustrate the increasing interest in, and value of, the scientific and practical applications and contacts of geophysics--nationally and internationally.

J. A. Fleming, General Secretary

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

GENERAL ASSEMBLY

Washington, D. C.
April 27, 1934

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PROGRESS IN DEVELOPMENT OF THE UNITED STATES WEATHER SERVICE IN LINE WITH THE RECOMMENDATIONS OF THE SCIENCE ADVISORY BOARD

Willis Ray Gregg

The Science Advisory Board, which acts under the jurisdiction of the National Academy of Sciences and the National Research Council, was created by order of President Roosevelt on July 31, 1933. This Board was given authority "to appoint committees to deal with specific problems in the various departments." One of the first committees so appointed was the "Special Committee on the Weather Bureau." Its members are: Robert A. Millikan, Director, Norman Bridge Laboratory of Physics, and Chairman of the Executive Council, California Institute of Technology, Pasadena, California, Chairman; Isaiah Bowman, Chairman, National Research Council, and Director of the American Geographical Society, New York City; Karl T. Compton, President, Massachusetts Institute of Technology, Cambridge, Massachusetts; and Charles D. Reed, Senior Meteorologist-in-Charge, Weather Bureau Section Center, Des Moines, Iowa.

This Committee submitted a report, based on a very thorough inquiry and study in December 1933. The report contains a number of recommendations, the two most important being (1) an extension of the air-mass analysis method of forecasting, and (2) consolidation of weather- and communication-service under the Weather Bureau.

Naturally, in so brief a period as has elapsed since the submission of this report, it has been possible only to make a beginning toward putting these and other recommendations into effect. Furthermore, the Special Committee itself, in its report, has sounded a note of caution against too precipitate a change from the old, well-established, and quite efficient methods of forecasting to the newer, so-called "air-mass analysis" method. It was suggested that the transition might well take place in the course of something like five years. This present statement must therefore be confined largely to an expression of what we hope to accomplish, together with an outline of such portions of the program as it may be possible to undertake in the near future.

(1) Air-mass analysis--At the outset it should be emphasized that there is nothing particularly new in the "air-mass analysis" concept of forecasting. It has been quite fully understood for many years, but its effective application has not been possible, because it requires a greater wealth of observational material than has heretofore been available. In a paper to follow this one the chief features of the theory, together with some examples of its practical use will be presented. Suffice it to say here that air-mass analysis consists, in brief, of a detailed study of masses of air of decidedly different structure as to temperature, moisture, and wind that meet along an irregular line variously referred to as a "discontinuity-line," "polar front," "wind-shift," etc. These masses of air, cold and dry from polar regions, warm and humid from equatorial, do not readily mix but tend to preserve their individual identities, the warm, moist air being forced to rise above and flow over the denser cold air, with resulting condensation and precipitation and other attendant phenomena which give us most of the stormy weather characteristic of temperate latitudes.

It will be seen at once that the chief requisite for such analysis is more detailed information concerning the structure of these conflicting masses of air. Accordingly, the first step in carrying out the recommendations of the Science Advisory Board was the formation of an interdepartmental committee to determine what could be done along this line through cooperation. It is gratifying to be able to report that, as a result of this committee's recommendations, which have been approved by the Secretaries of the Departments concerned, there will be, beginning July 1, 1934, some 20 stations at which regular daily airplane-flights will be made to a height of about five kilometers. These stations, comprising approximately an equal number operated by the Weather Bureau, by the War Department, and by the Navy Department, are quite well distributed over the country. The flights will be made at essentially the same time at all of them. In addition, at certain other stations and also on seven Naval ships occasional flights will be made during daylight hours, and the data from these flights will be of considerable value, even though not representing conditions at the times of the regular daily flights.

Thus, on July 1, 1934, a very definite beginning will be made in securing data necessary for the extension of air-mass analysis in forecasting. Twenty stations will not be sufficient, but they at least mark a definite step toward the ultimate goal.

A very important feature of the whole program is an increase in the number of country-wide collections of reports of surface-conditions from two to four each day. The details have been worked out, and it is hoped to put this enlarged service into effect in the next year or so, although no definite statement in the matter is yet possible.

(2) Communication-service--With regard to the second major recommendation of the Science Advisory Board, that of consolidating weather- and communication-service under the Weather Bureau, it can only be said at this time that the matter is receiving thorough and careful study by an interdepartmental committee. Its report and recommendations will almost certainly be submitted within the next two or three months.

Other recommendations of the Science Advisory Board are being given consideration, and will be put into effect as rapidly as practicable. Some of them will necessarily have to await the further development of plans for the extension of air-mass analysis, such, for example, as the decentralization of the general forecast work, special training of qualified personnel, and better location of observational stations. As to the last point, the Weather Bureau has already adopted a policy of making airports the official observational stations wherever it is practicable and desirable to do so. Three such changes have been made recently and others are under consideration.

In conclusion it is desired to point out again that the Science Advisory Board's report was definitely adopted as a basis for future development only three months ago, that is, early in February 1934. During this period the carrying out of the program has been outlined in detail, including arrangements for cooperation with other departments and requirements for additional personnel and other facilities. One very important feature of the program--additional airplane-stations--will begin July 1, 1934. There seems to be no reason to doubt that all of the program will be in effect within the five-year period specified, and much of it within the next year or two.

U. S. Weather Bureau,
Washington, D. C.

THE USE OF AEROLOGICAL OBSERVATIONS IN WEATHER-FORECASTING

H. C. Willett

During the last fifteen years the so-called polar-front or air-mass analysis methods of weather-map analysis and weather-forecasting have come into general recognition in all the leading meteorological services. The new air-mass and front concepts are finding a place in the meteorological literature and synoptic practice, in more or less modified form, in every country in which there is maintained any contact with modern meteorological trends. At the same time it is certainly true that the technique of application of these methods to the daily synoptic routine, in the preparation of weather-forecasts, still falls far short of the maximum possible effectiveness. This is particularly true of the acquisition and utilization of observations from upper levels of the atmosphere for the purpose of giving our surface weather-map analysis a third dimension.

Weather-map analysis and weather-forecasting by the air-mass analysis method are based on only two essentially simple concepts, (1) the air-mass, and (2) the front. Air-masses are the large rather uniform air-currents, originally of either polar or tropical origin, which possess characteristic properties in the form of distinct differences in temperature, moisture-content, and vertical stability--properties which depend on the source and trajectory of the mass.

Fronts are the transition-zones of rapid horizontal change of the meteorological elements between air-masses. They are usually treated as atmospheric discontinuities. The air-masses which occur in a given region may be classified into definite characteristic types which depend upon the source-region and the trajectory of the particular mass. Fronts may be classified according to the air-mass types which they separate and the relative motion of these masses.

The weather which is experienced at a given point depends upon the sequence of air-mass and front passages occurring there. Within one and the same air-mass the weather depends not only upon the surface-conditions of temperature and moisture, but even more upon the vertical distribution of these elements within the air-mass. Upon this vertical structure of the air-mass depend the following important weather-phenomena:

(a) The structure of the wind, whether stratified and smooth in flow, or convectively turbulent and gusty.

(b) The presence or absence of cloud-forms, and if present whether of the low-stratified type with poor visibility and fog, or of the higher convective type with good surface-visibility.

(c) The occurrence or non-occurrence of precipitation, and if present whether of the mist-and-drizzle type, or of the convective-shower and snow-flurry type.

(d) The degree of horizontal visibility, whether reduced by the accumulation of dust, smoke, or fog near the ground, or improved by the rapid vertical transport and dispersion of these obscuring elements throughout the atmosphere.

In the vicinity of the front, or transition-zone between air-masses, the weather depends upon the interaction of the air-masses. The broad zones of cloudiness and precipitation which accompany cyclonic activity, as well as line squall and related phenomena, are directly associated with front passages and frontal activity. Even the genesis, deepening, and filling of the cyclones themselves depend upon this frontal activity, or air-mass interaction, and the properties of the air-masses involved. Differences in moisture-content, temperature, and vertical stability as well as the slope of the front and the relative movement of the interacting air-masses, are all important factors in determining the distribution and nature of the cloudiness and precipitation in the vicinity of the front, and in supplying the necessary available energy for active cyclogenesis.

It is evident then, that the weather experienced at any point, depending as it does upon the sequence of air-mass and front passages, is determined to a large extent by the vertical distribution of the air-mass properties and the vertical structure of the fronts. Consequently for the most effective application of the air-mass analysis methods to the problem of weather-forecasting, special emphasis must be placed on the collection and comprehensive analysis of meteorological observations from upper levels in the atmosphere. Up to the present time the problem of developing an efficient routine procedure for the treatment of aerological observations in regular forecasting work has received little attention. During the earlier period of the development of the polar-front theory by the Norwegian meteorologists, almost no direct aerological observations were available. The analysis of the weather-map, that is, the identification of the air-masses and tracing of the fronts at the ground from day to day, was based entirely on surface-observations. The interpretation of what was taking place at upper levels was of necessity rather hypothetical, as it was usually based on the current conceptions of ideal frontal and cyclonic structure.

As the air-mass analysis procedure was more widely adopted, especially in regions where observations of winds aloft and aerological soundings were available, the attempt was made to make more use of this material in the routine analysis and interpretation of the daily weather-map. Winds at upper levels are usually represented on one set of charts, and aerological soundings, when available, are worked up individually in one or another of the standard graphical forms. However, it can certainly be said that up to the present no satisfactory routine method has yet been developed for the complete utilization and correlation of such observations with those of the surface-map. Hitherto, available aerological material everywhere has been too scanty even to offer the possibility of the completion of our daily surface weather-map analysis in the third, or vertical, dimension.

Although no effective routine method of treating the daily aerological observations has been developed, there has grown up a method of handling such material in special cases chosen for detailed investigation when observations are particularly numerous or frequent. This method is simply to plot in a vertical cross-section through the particular phenomenon being investigated the distribution of the various meteorological elements, and then on the basis of this distribution to sketch in the discontinuity-surfaces or fronts, and thus to complete the picture of the atmospheric structure in the given instance. Such cross-sections through fronts or cyclones may be based on either simultaneous observations from a line of stations, which gives a true picture of the instantaneous structure of the atmosphere along the chosen line, or on a sequence of soundings at a single station, in which case we get a moving picture of the structure of the atmosphere as it advances over a fixed point. These two methods may be combined in case the atmospheric structure and movement is steady, but this procedure must be followed cautiously. Such atmospheric cross-sections are particularly valuable when sounding-balloon observations make possible the extension of the representation through the tropopause into the stratosphere, although much of real value also may be determined when the height is restricted to five or six kilometers.

The plan which is at present being worked out by the Weather Bureau, with the cooperation of the Army and of the Navy, for a greatly enlarged network of airplane aerological stations, should make the United States the best region in the world in which to apply the air-mass analysis methods of weather-map analysis and weather-forecasting. This is especially true for the very important problem of applying aerological observations more effectively in the routine practice of weather-forecasting. If the present Weather Bureau plan of a network of aerological stations is eventually extended to include three or four sounding-balloon stations, and a like number of mountain-summit stations, and if it can be seconded by the establishment of just a few regular cooperating aerological stations at strategic points on the part of Canada to the north, the result will be the almost ideal layout for the investigation of atmospheric phenomena for which both the practical weather-forecaster and the theoretical worker in atmospheric dynamics and thermodynamics have long been waiting.

If one considers a little more closely the problem which faces the synoptic meteorologist who is to handle in the near future the observational material from the greatly extended network of aerological stations, it quickly appears that the problem resolves itself into two distinct parts, namely, (1) to develop a quick practical method for the daily routine analysis of the data for use in preparing the regular forecasts and (2) to develop methods for the thorough investigation, in the light of all obtainable data, of meteorological conditions of particular interest.

It is evident that if the principal weather-forecasts of the day are to be based on the early morning observations, so that the aerological ascents must be completed and the reports received at this early hour, any treatment of these data which is to be of use to the forecaster must be simple and quick. Only airplane-soundings and regular observations from mountain-summit stations can be quickly enough available for this purpose. On the other hand, we have seen how important it is, even for the routine forecasting-service, that our present two-dimensional weather-map analysis be given some more comprehensive third-dimensional extension. Therefore, an attack on this problem will have to be given some serious consideration. But probably the best solution of the problem will be reached only after extended work on the second problem mentioned above, that of the detailed investigation of numerous synoptic situations of particular individual interest.

Investigations of this special type should include both the determination of the typical air-mass properties, and the study of frontal and cyclonic structure by means of atmospheric cross-sections. These are purely research problems, to be carried on quite separately from the routine forecast-work, but such research will be of fundamental importance to the development of the forecasting routine. These investigations must be carried out leisurely and thoroughly, making use of all possible data, preferably including daily or short-interval series of sounding-balloon ascents, and continuous automatic records from a few selected mountain-summit stations, such as those now being taken on Mount Washington.

The determination of the characteristic properties of the principal air-mass types is in itself a straightforward statistical problem in which superficial work has been done both in Europe and in the United States. But the real difficulty in this problem up to the present has been the frequent uncertainty, due largely to scanty aerological observations and vessel reports, of the analysis on which the identification of the very air-masses being investigated is based. This is especially true at upper levels where the transition from one air-mass to another cannot always be recognized with certainty from a single aerological ascent. Consequently much remains to be done in this field for which increased aerological observations are necessary. Furthermore, the whole problem of the quantitative explanation of the observed air-mass properties and their modifications in terms of radiation, conduction, evaporation, condensation, convection, and other factors, remains almost untouched as yet.

Only a very few detailed atmospheric cross-sections, and those with relatively insufficient aerological data, have been worked up hitherto. It is only through the careful preparation of a large number of such cross-sections or other similar diagrammatic representations of atmospheric conditions throughout the troposphere that we can hope ultimately to be able to give quantitative explanations of most of the more complicated atmospheric processes, and in particular that of cyclogenesis. Only through extensive comparative work of this kind can we hope to find reliable dynamic or thermodynamic criteria by which to foretell accurately the trend and rate of the cyclonic development, and the distribution of precipitation, to be expected in many of the synoptic situations to which we as yet can apply not much more than guess work. Obviously the development of the routine methods of handling aerological material in the daily forecast-service will also depend on research of this type, for only through investigation of this kind can the experience be obtained which will indicate the factors of most importance in considerations of forecasting. At present the outlook in this country for a real advance during the next few years in the problem of weather-forecasting is definitely hopeful. The necessary aerological data will probably be available. All that seems necessary is to find qualified men with time to devote to the problem of the application of these data to forecast-problems.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

COMPLETE WEATHER-MAPS OF THE NORTHERN HEMISPHERE IN RELATION TO STUDIES OF MOVEMENTS OF MAJOR AIR-MASSES

C. L. Mitchell

For many years it has been the desire of meteorologists to secure and plot daily meteorological data from all parts of the Northern Hemisphere. During the first International Polar Year, 1882-83, observations were made at a number of stations in high latitudes, but the daily weather-charts of the Northern Hemisphere for this period, published subsequently, were unsatisfactory, and presented a far from complete picture of weather-conditions for the Hemisphere.

The daily weather-maps published by the Deutsche Seewarte, containing data from numerous vessels as well as from all land-areas from which reports were available, have been the most comprehensive of any daily weather-maps for a long time.

The interest in outbreaks of air from the polar regions has been much greater since the World War, and, with the perfection of short-wave radio sending apparatus, the number of observing stations in North America has increased materially, and a few stations have been established in northern Siberia. However, no reports are received, except in rare instances, from any stations above the Arctic Circle between Cape Chelyuskin, located at longitude 104° east, and Point Barrow, longitude 155° west. This leaves a vast and important area from which no current reports are yet available for the detection of the possible outflow of polar air-masses that may later vitally affect the weather-conditions in North America.

On January 1, 1933, the Soviet Government began publishing at Moscow a large daily weather-map with Eurasia, northern Africa, and adjacent waters on one side, and the entire Northern Hemisphere on the other, together with a separate four-times-daily compilation of data for a large number of stations in Europe and Asia. It has long been the desire of Weather Bureau forecasters to make an intensive study of the weather and changes therein from day to day over the entire Northern Hemisphere in order to obtain a much more complete knowledge of the interrelations of the various air-masses of either polar or tropical origin. With this increased knowledge, progress can assuredly be made in making forecasts more accurate and for a longer period ahead. Consequently, in planning for sub-projects under the Weather Bureau project of the Civil Works Administration, opportunity was afforded for the employment of two men for the purpose of entering on our Northern Hemisphere charts data from foreign maps. Few reports are received currently from Asia, northern Africa, European Russia, the Balkan States, and the western Pacific Ocean. By utilizing the reports for these areas found on the daily weather-maps published at Moscow, Kobe, Zi-Ka-Wei, Calcutta, Cairo, and Algiers, we were enabled to secure a sufficient number of reports for much the greater part of each of these areas. As stated previously, four reports each day are published in the Moscow weather-bulletins, so that both a.m. and p.m. observations for Siberia and eastern Europe were entered on our charts. During the past five months the Civil Works Administration workers have completed entry of data for the first half of the year 1933. With the addition of the selected reports entered by these men, the total number of reports on the completed chart of the Northern Hemisphere on a typical map, that of February 27, 1933, was 550. Of these, 409 reports were from land-stations and 141 from vessels. It was hoped to have maps for one entire year completed before the work was discontinued. Unfortunately, insufficient help was available for completion of the project.

After entry of all available data, considerable time is required for completion of the isobars for the additional areas, for the entering of 24-hour pressure-changes, and for the plotting of the tracks of all cyclones and anticyclones of the entire Hemisphere. Assistance and time have been available to date for the completion of the twice-daily charts for January, February, and March, 1933. Consequently, study of the varying weather-situations for only three months (and this study has been far from thorough) does not permit of drawing conclusions that are necessarily applicable to all seasons and all years. However, the following tentative conclusions may be of interest:

(1) When pressure becomes high over practically the entire polar region, the usual interchange of cold and warm air does not take place freely, so that, for the time being, storm-development and movement are slowed down in the temperate zone. Such a period embraced the last few days of February and the first days of March, 1933.

(2) When pressure is high over northern North America and also over the Kamchatka to Sea of Okhotsk Area, the Pacific cyclones are likely to move northward to or over Alaska, but with low pressure over the Kamchatka Region, pressure is likely to remain high over northern Alaska; consequently, the Pacific cyclones will, under these conditions, move eastward and enter the North American Continent over British Columbia or southeastern Alaska. These different courses of the Pacific cyclones materially affect the weather and changes therein over at least the western and central parts of the United States.

(3) When cyclones move eastward over the Mediterranean Area, secondaries tend to develop over southern Egypt, at times near latitude 10° north, and move eastward or northeastward toward the Red Sea. No comparable condition is found in the Western Hemisphere, perhaps because of the lesser land area south of latitude 30°.

Pressure-graphs were made for selected arctic stations, utilizing Okhotsk and Petropavlask in the absence of reports from more northerly stations in the area referred to between Cape Chelyuskin and Point Barrow. With the aid of these graphs which were of material assistance in predicting the outbreak of polar air-masses, or the more or less stagnant condition of such air-masses, together with a very brief study of the Northern Hemisphere charts, forecasts for a week ahead were hastily made for Washington, D. C., based on each Saturday morning's map during January, February, and March, 1933. These forecasts verified sufficiently well to indicate the great importance of quite complete Northern Hemisphere weather-maps in identifying and tracing the movements of major air-masses.

U. S. Weather Bureau,
Washington, D. C.

PRELIMINARY REPORT ON RELATIONSHIP BETWEEN TEMPERATURES IN THE UNITED STATES AND PRECEDENT PRESSURES OUTSIDE THE UNITED STATES

R. Hanson Weightman

A number of different avenues of study have shed light on the problem of long-range forecasting. If we may judge from the results achieved thus far in a practical way, the most profitable one is to associate weather in one locality with antecedent conditions in some other distant region, as was done by Sir Gilbert Walker in the monsoon-forecasts for India. Unfortunately little work of this character has been done in the United States and it was with the idea of laying a foundation for studying conditions in this country that the work which will be described was undertaken.

With a medium so labile and so subject to change as our atmosphere, it would be idle to suppose that some extremely simple relationship connected the weather in a nearby region with antecedent weather in some remote region. It was realized, therefore, that chances were extremely remote that the results of this investigation would expose any such simple relationship. Nor was it with the expectation of solving finally the problem of long-range forecasting in this country that the study was undertaken but rather with the conviction that by such studies our knowledge would be enhanced, with the likelihood of developing suggestions that would lead by successive stages to a solution of the problem in the future.

For the purpose of the present investigation, the United States was divided into twelve districts. Ten stations were used in each district, except in districts 8, 11, and 12, in which cases five stations were employed. Temperatures were grouped by quarters or seasons. The winter was represented by the months of December, January, and February, spring by March, April, and May, summer by June, July, and August, and fall by September, October, and November. While twelve districts may seem a large number, it was apparent that it would be easier at some future time to combine small districts than to break down large ones.

Pressure data for 63 foreign stations were taken for the most part from World Weather Records (1928 edition), published by the Smithsonian Institution, and from a page-proof of a new edition of that publication which was furnished through the courtesy of the Editor. Stations were carefully selected on the basis of length of record and geographic distribution. Both Northern and Southern hemispheres were covered as well as possible with the data available.

The work on District 1, the North Atlantic States, had been completed when the additional work under the Civil Works Administration was undertaken. Under the Civil Works Administration six other districts have been completed.

The temperature-departures for each of the seven districts have been compared with precedent pressure-departures at 63 foreign stations. For each season for each district there are involved three set-ups. For example, winter temperatures in District 1 were compared with foreign pressure-departures first, one quarter before, involving September, October, and November of the preceding year; second, two quarters before, comprising June, July, and August of the preceding year, and third, three quarters before, involving March, April, and May of the preceding year.

Comparisons were made by means of correlation-coefficients and thus far more than 5000 coefficients have been worked out. The coefficients of correlation have been entered on world-charts and lines of equal positive and negative correlation drawn, three charts for each of the four seasons--in all twelve charts to each district. The positive correlations and the negative correlations fall into groups, with maximum values near the centers. As an illustration, I will describe the essential features of two of the charts, the first portraying a comparison of winter temperatures in District 1, with pressure-conditions two quarters before, and the second, of winter temperatures in the same district with pressure-conditions three quarters before. In the first, large negative coefficients are shown extending from the north Pacific Ocean southeastward to the northern half of South America, with a maximum coefficient of -0.48 at Midway Island and -0.30 at Colon, while a moderately well-developed positive area covers southern and east-central Africa and the Malay Archipelago. On the second chart, showing conditions three quarters before, marked positive correlations extend from the northwestern North Pacific Ocean south and southwestward to Australia and thence westward over the Indian Ocean to east-central Africa, with a maximum of +0.51 at Batavia. There is noted also a fairly well-marked negative area over central and eastern Canada and western Greenland, with a maximum of -0.36 at Moose Factory.

Up to the present time it has been impossible to complete the other five districts in this survey of temperature, nor has it been possible to even begin a study of the precipitation in any of the twelve districts. Pressure-departures only have been used as the antecedent index. It would be desirable to use temperature and precipitation as antecedent indexes as well.

The work so far is only preliminary, since after the simple correlation-coefficients have pointed to the remote regions in which pressure-conditions apparently exert an influence on the subsequent temperature in the United States the next step will be to bring several such relationships to bear simultaneously on a selected region in the United States through the use of multiple correlation-coefficients.

It is proposed to publish the results of this investigation in some detail in the Monthly Weather Review during the present year. We contemplate giving the temperature-departures by districts and the precipitation-departures as well. Pressure-departures for foreign stations will also be presented. In addition, a table will show the relative areas of the twelve districts, in order that investigators may have the means to combine them in any way desired. By making available the tools with which to work, it is hoped to inspire further and more searching investigations of this kind not only by Weather Bureau personnel but by research workers outside the Weather Bureau in both scientific and commercial fields.

U. S. Weather Bureau,
Washington, D. C.

PRELIMINARY REPORT ON THE UPPER-AIR WORK UNDERTAKEN IN CANADA DURING THE SECOND INTERNATIONAL POLAR YEAR

J. Patterson

(Abstract)

As part of the Canadian contribution to the Second International Polar Year activities, the Meteorological Service of Canada carried on an intensive observational program on the temperature and movement of the atmosphere at three stations in Arctic Canada, namely, Chesterfield Inlet (latitude 63° 45' north in longitude 91° 50' west), Cape Hope's Advance (latitude 61° 05' north in longitude 69° 33' north, and Coppermine (latitude 67° 47' north in longitude 115° 15' west).

A grand total of 1556 pilot-balloon ascents at these three stations were observed beyond 0.5-km altitude. During the winter season (December to February) 117 ascents were observed to two km, and 297 ascents during the summer. The upper winds were approximately constant (±1 m/sec) from the surface to 4-km altitude and varied little in strength from season to season. The approximate wind-velocities up to 3 km were: Cape Hope's Advance 9.0 m/sec; Chesterfield Inlet 8.2 m/sec; Coppermine 7.0 m/sec. (The mean annual wind-velocity at Drexel, Nebraska, at 2-km altitude is 13 m/sec.) The surface-winds are relatively very strong at the northern stations, for example, mean hourly wind-velocity Cape Hope's Advance 18.5 mi/hr = 8.4 m/sec, compared with 8.6 mi/hr = 3.8 m/sec at Toronto, based on all hourly values scaled from twelve months' anemograph-records.

Northwest winds predominated at all stations throughout the year. During the summer the winds turned more northerly at Cape Hope's Advance and Coppermine and more southerly in autumn and winter especially at higher altitudes.

The temperature-difference between two Stevenson screens, one about 1.25 m above the Earth's surface and the other at the top of a mast 30 m higher, was measured continuously by thermocouples at Coppermine and at Chesterfield Inlet. In winter at Chesterfield, the temperatures at the top of the mast were consistently higher, the

excess averaging 1°.23 C for the 24 hourly values during February. For brief periods about 5 a.m. on January 19, 1933, the temperatures at the top of the mast were as much as 7°.4 C warmer. Even greater inversions exceeding 15° C--the scale-limit--were recorded at Coppermine. During the summer months the temperatures at the top of the mast about noon were lower than in the surface Stevenson screen, but continued higher during the night.

A total of 145 kite-flights over 150 m in height were made at Chesterfield Inlet, and at Coppermine, of which approximately 60 per cent showed considerable temperature-inversions.

Three Moltchanoff radiosondes were successfully released at Coppermine. One reached the stratosphere on March 4, 1933, at an altitude of 8.5 km, and a minimum temperature of -38° C at the tropopause. The records from the balloon-sondes at Goderich and Calgary indicated a large annual variation in the height of the tropopause over southern central Canada. Based on the mean of the values obtained at both stations the tropopause has its minimum height of 6.5 km in February, and its maximum height of 13.5 km in September.

Meteorological Service of Canada,
Toronto, Canada

UPPER-AIR WINDS OVER NORTHERN ALASKA DURING THE POLAR YEAR, AUGUST 1932 TO AUGUST 1933

Loyd A. Stevens

The United States Weather Bureau is now engaged in the preparation of some 25,000 pilot-balloon summary forms for the Second International Polar Year Commission. On these forms are entered the data from all Weather Bureau pilot-balloon stations including one in Puerto Rico and four in Alaska for the period August 1932 to August 1933, inclusive. Since the International Commission is especially interested in observations in and near the polar regions, the Weather Bureau established, and maintained for the greater portion of the Polar Year, a special meteorological station at Point Barrow--the northernmost point of land in Alaska, located at latitude 71° 23' north in longitude 150° 17' west. Along with other important observations, pilot-balloon observations were made twice daily, weather permitting, from September 14, 1932 to August 11, 1933, inclusive. During this period a total of 580 observations were made--88 per cent of the total scheduled. Of the 580 observations made, 473 reached one km, 276 reached three km, 108 reached 5 km, and 15 reached 10 km. The highest single observation was made on July 9, 1933, when an altitude of 12.5 km was attained. The wind at that point was north-northeast at 15 meters per second. The highest velocity recorded during the entire period was 41 meters per second from the west on October 7, 1932.

It is the purpose of this paper to make a brief analysis of the pilot-balloon observations during the Polar Year at Point Barrow and also, by way of comparison, of those made at two other regular Weather Bureau stations located at Nome and Fairbanks, Alaska, respectively. At these latter two stations pilot-balloon observations have been made continuously since August 1930.

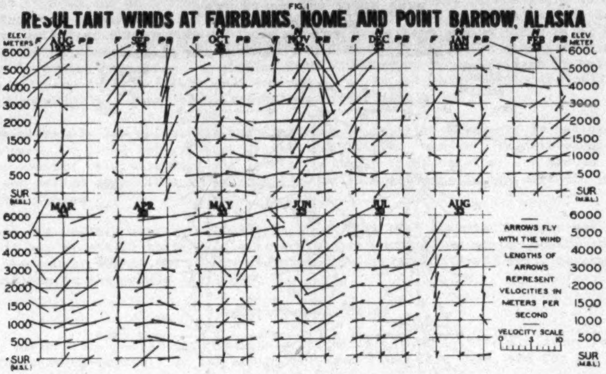
The analysis consists of (1) resultant winds by months and for the year, (2) wind-roses for the Polar Year as a whole, (3) average velocities, and (4) the frequency of different velocities for the months of January and July, and for the year.

Resultant winds

Since resultant winds, based upon a sufficient number of observations, indicate the true mass-movement of the atmosphere, they are shown here in some detail for these stations, being given for all standard levels by months and for the year. The monthly resultants are shown for levels up to six kilometers in so far as data are available, and the annual values are given for the two additional levels of 7 and 8 km. In some cases the number of observations for an individual month was small and some apparent inconsistencies and irregularities resulted, but in general the air-movement over this

FIG. 1

RESULTANT WINDS AT FAIRBANKS, NOME AND POINT BARROW, ALASKA



area is believed to be indicated quite accurately in the accompanying charts on which the resultants have been drawn (Figs. 1 and 2). It is apparent that easterly winds predominate below three km at all three stations during the greater portion of the year. This may be attributed to the influence of the Aleutian Low-Pressure Area usually centered to the west or southwest of Alaska which is the dominant pressure-area in that region. During midsummer, however, the Aleutian Low is rather weak and a stronger area of high-pressure builds up over the North Pacific. The effects of this pressure-distribution is reflected in the westerly resultants which prevail during June, July, and August. Above three kilometers the resultants are in general from the west.

It will be noted that the shift from easterly to westerly resultant directions occurs between two and three km at Point Barrow and at Fairbanks, and between five and six km at Nome. This is probably due to the fact that the center of the Aleutian Low is on the average nearer to Nome than to the other two points.

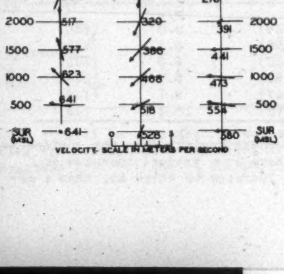
FIG. 2

RESULTANT WINDS FOR POLAR YEAR

AUG 1932-AUG 1933

ARROWS FLY WITH THE WIND

LENGTHS OF ARROWS REPRESENT VELOCITY



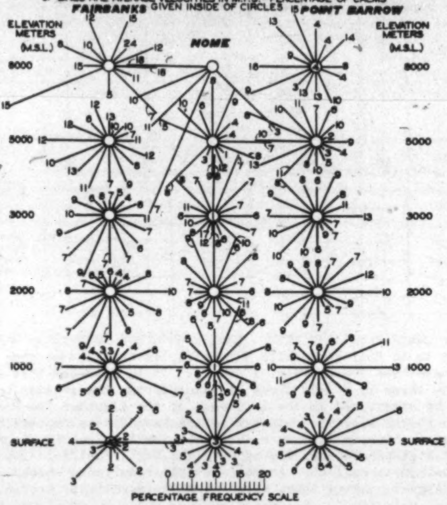
The resultant wind-directions compare favorably with the average pressure-maps for the North Polar regions shown by Sir Napier Shaw in Volume 2 of his Manual of Meteorology (pp. 216-266).

Resultant velocities are, for the most part, rather light, especially as compared with those stations in the middle latitudes, thus indicating relatively less atmospheric movement in this region than in the middle latitudes.

Wind-roses

In Figure 3, wind-roses are given for the Polar Year as a whole. It will be noted that for the lower levels the most frequent wind-directions observed are between east and southeast at Fairbanks, east or east-northeast at Point Barrow, and between north and northeast at Nome. A shift to westerly prevailing winds occurs on the average at about two km at Fairbanks, and between two and three km at Point Barrow. At Nome, however, this shift does not occur until a level between four and five km is reached. At five km the most fre-

FIG.3
WIND-ROSES FOR POLAR YEAR
AUG 1932 - AUG 1933
LENGTHS OF LINES INDICATE PERCENTAGE FREQUENCY-NUMBERS AT END OF LINES ARE AVERAGE VELOCITIES IN M.P.S.-PERCENTAGE OF CALMS GIVEN INSIDE OF CIRCLES



quent directions recorded are west at Fairbanks, west-northwest at Point Barrow, and southwest at Nome. At eight km the most frequent directions are west-southwest at Fairbanks and at Point Barrow, and south-southwest at Nome. It should be pointed out here, however, that only six observations reached eight km at Nome and that the wind-rose for this level is probably not representative of average conditions.

In general highest velocities occur with the prevailing directions but the difference in velocity is not large between the prevailing directions and directions less frequently recorded.

Average velocities

Average velocities in meters per second for the Polar Year together with the number of observations on which the averages are based are given in Table 1. These values are obtained by dividing the total of all velocities by the total number of observations.

Table 1--Summary of average wind-velocities and number of observations, Polar Year of 1932-33

Height	Fairbanks		Nome		Point Barrow	
	Average velocity	No. observations	Average velocity	No. observations	Average velocity	No. observations
km	m/s		m/s		m/s	
Surface	1.5	(641)	3.5	(528)	5.0	(580)
1	6.2	(623)	6.3	(468)	9.2	(473)
2	7.3	(517)	7.7	(320)	8.8	(391)
3	7.9	(384)	7.9	(181)	8.7	(276)
5	11.1	(153)	7.3	(47)	9.1	(108)
8	12.8	(23)	9.3	(6)	10.4	(28)

It will be noted that the average velocities increase rapidly from the surface to one km at all stations. Above one km at Fairbanks there is a gradual increase in velocity up to eight km. At Nome there is a gradual increase to three km, then a decrease at five km and an increase again at eight km. At Point Barrow there is a decrease from one to three km and an increase again from three to eight km. It is of interest to note that the drop in velocity at five km at Nome and at three km at Point Barrow coincide closely with the average height at which the shift occurs from easterly to westerly prevailing winds. A similar drop in velocity is not evident at Fairbanks but the increase in velocity between two and three km (at which height the shift occurs) is notably less than the change between other levels.

The extremely low velocities and frequency of calms at Fairbanks is believed to be due, in part, to local topography. It should be stated, however, in this connection that the average velocities for all levels for these three stations are two to three meters per second lower than those for pilot-balloon stations in the northern part of the United States.

From the monthly average velocities (which have been computed but are not shown here), it may be stated that velocities are highest during the winter months and lowest during the summer months, but the seasonal variation is relatively small as compared with stations in the middle latitudes.

Velocity-frequencies

In Table 2 the percentage frequencies of different velocities are shown for standard velocity-groups, for the months of January and July 1933, and for the year.

Table 2--Percentage frequency of velocities in meters per second in different velocity-groups (highest percentages are underscored)

Station	January						July						Year					
	0-1	2-7	8-14	15-21	>21	No. obs'ns	0-7	2-7	8-14	15-21	>21	No. obs'ns	0-1	2-7	8-14	15-21	>21	No. obs'ns
							At surface											
Fairbanks	93	7	..	..	..	45	41	51	8	..	..	49	64	34	2	..	..	641
Nome	21	64	15	..	..	43	24	73	3	..	..	37	21	66	12	1	..	528
Point Barrow	5	93	2	..	..	60	6	81	13	..	..	63	3	86	10	1	..	580
							At one kilometer											
Fairbanks	..	64	32	4	..	44	7	72	21	..	..	47	5	66	27	2	..	623
Nome	..	59	41	..	..	39	13	53	27	7	..	30	5	62	27	4	2	468
Point Barrow	2	51	33	7	7	57	2	42	39	15	2	54	2	40	43	11	4	473
							At two kilometers											
Fairbanks	3	55	36	6	..	33	8	65	22	5	..	40	7	55	31	6	1	517
Nome	7	38	41	14	..	29	5	58	26	11	..	19	2	48	42	8	..	320
Point Barrow	..	51	33	16	..	57	2	51	35	12	..	43	1	46	36	15	2	391
							At three kilometers											
Fairbanks	6	50	33	11	..	18	4	60	36	..	..	28	2	51	37	7	3	384
Nome	..	22	55	17	6	18	8	46	38	..	8	13	2	49	42	5	2	181
Point Barrow	2	46	35	15	2	46	3	46	42	9	..	33	2	46	38	13	1	276
							At five kilometers											
Fairbanks	..	33	67	..	..	3	..	50	50	..	..	6	3	34	42	15	6	153
Nome	..	..	100	..	..	2	..	40	60	..	..	5	9	45	40	4	2	47
Point Barrow	7	54	31	8	..	13	13	67	20	..	..	15	4	40	42	13	1	108
							At eight kilometers											
Fairbanks	..	..	..	..	..	0	..	..	..	..	..	0	..	36	36	5	23	23
Nome	..	..	..	..	..	0	..	..	..	..	..	0	..	33	50	17	..	6
Point Barrow	..	..	..	..	..	0	..	30	60	10	..	10	7	21	47	25	..	28

It will be seen that at the surface more than 85 per cent of all recorded velocities are between calm and seven m/s, the remainder falling in the group of eight to fourteen m/s. At one km the percentage of velocities of seven m/s or less for the three stations combined decreases to 52 per cent, while those between eight and fourteen m/s increase to approximately 32 per cent and those between fifteen and twenty-one m/s amount to approximately 6 per cent. At 5 km the percentages of velocities between 0 to 7 and 8 to 14 m/s are 45 per cent and 41 per cent, respectively, and those between 15 to 21 and over 21 are 11 per cent and 3 per cent, respectively.

It is apparent from Table 2 that in general a greater percentage of velocities fall within the higher brackets during January than during July, and also that there is a gradual increase with height of the percentage of velocities of 15 m/s and over.

Summary

In summary the following facts stand out from this study:

(1) The mass-movement of air in the region of northern Alaska is relatively small as compared with that for the northern part of the United States.

(2) Below 3 km, on the average, easterly winds are recorded most frequently, while at higher levels westerly winds prevail.

(3) Average wind-velocities for this region, both surface and aloft, are 30 to 40 per cent lower than for points in the northern part of the United States.

(4) Individual recorded velocities do not deviate greatly from the average.

Since northern Alaska is a heretofore uncharted region as far as upper-air winds are concerned, it is hoped that this study will contribute something of value to our knowledge of the general circulation of the atmosphere.

U. S. Weather Bureau,
Washington, D. C.

MOUNT WASHINGTON'S CONTRIBUTION TO THE SECOND INTERNATIONAL POLAR YEAR

Salvatore Pagliuca

At its Locarno meeting in October 1931, the International Meteorological Committee adopted a resolution emphasizing the great importance of observations at mountain stations during the Second International Polar Year [see reference 1 at end of paper]. Mount Washington was the only high-level station in this country to cooperate with the International Polar Year Commission (see Figs. 1 and 5). The history of its organization and the details of its operation were outlined by R. S. Monahan and S. Pagliuca at the fourteenth annual meeting of the American Geophysical Union in April 1933 [2]. A popular account by R. S. Monahan has also appeared [3].

Owing to difficulties necessarily connected with the organization of such a major project on a strictly voluntary basis, it was not possible to start complete observa-

Titles of Figures 1 to 8

Fig. 1--The Mt. Washington Observatory in April 1933

Fig. 2--The shelter for thermometer and hygrometer, including maximum and minimum thermometers, sling-psychrometer, and thermohygrographs (photograph by Harold Orne)

Fig. 3--Making observations with nephoscope (photograph by Harold Orne)

Fig. 4--Pilot-balloon work; at left a shielded rain-and-snow gauge (photograph by Harold Orne)

Fig. 5--Observer on roof clearing heated anemometer structure of rime; cloud-observing at left, Eppley pyrheliometer for total solar and sky radiation on post at right (photograph by Harold Orne)

Fig. 6--Electrically heated anemometer on roof of Observatory (photograph by Harold Orne)

Fig. 7--Electrically heated wind-vane and hot-air-heated anemometer (photograph by Harold Orne)

Fig. 8--The ultra high-frequency radio station on Mt. Washington, Alexander A. McKenzie in charge (photograph by Harold Orne)

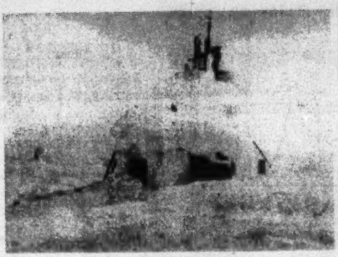


Fig. 1

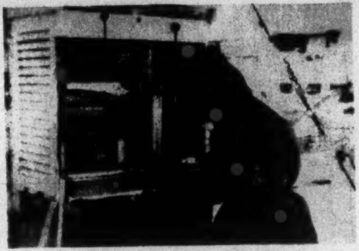


Fig. 2

Fig. 3

Fig. 4

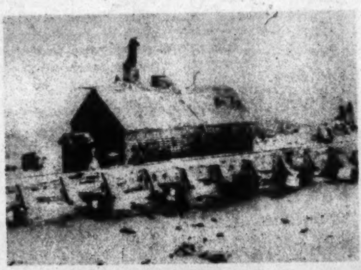


Fig. 5

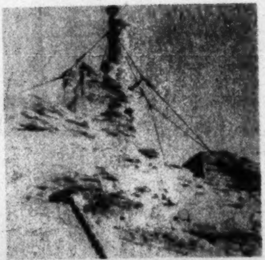


Fig. 6

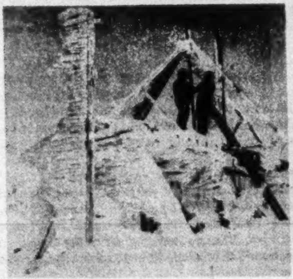


Fig. 7

Fig. 8

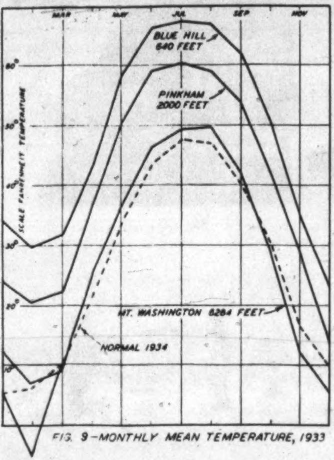


FIG. 9—MONTHLY MEAN TEMPERATURE, 1933

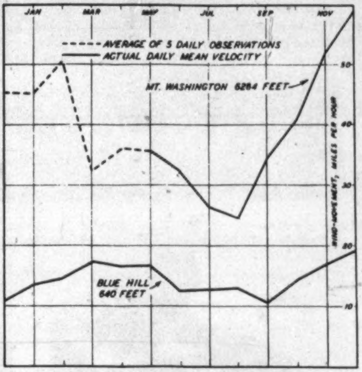


FIG. 10—MONTHLY AVERAGE HOURLY WIND-MOVEMENT, 1933

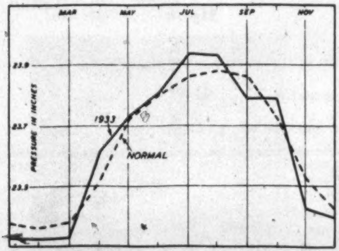


FIG. 11—MONTHLY VARIATION ATMOSPHERIC PRESSURE, MT. WASHINGTON, N.H. (ALTITUDE OF BAROMETER, 6270 FT.)

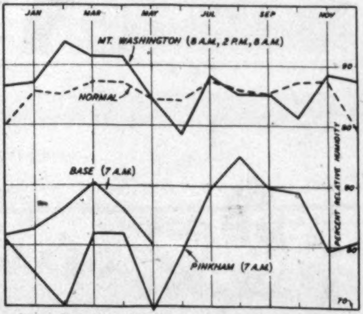


FIG. 12—MONTHLY VARIATION OF RELATIVE HUMIDITY, 1933

tions before November 18, 1932. All of the meteorological elements recommended by the Polar Year Commission were recorded at a minimum of six times daily. During the first-order days, hourly observations were made to assure greater accuracy and continuity of records.

Continuous records of atmospheric pressure, air-temperature, and relative humidity (Fig. 2) and of solar and sky-radiation (Fig. 5) were obtained by means of standard direct-reading and self-recording instruments. Nephoscopic observations of clouds were made regularly (Fig. 3). A total of 164 pilot-balloons were released from the summit during the Polar Year (Fig. 4). Two comparison stations were maintained at the west and east bases of the mountain.

In a paper presented by the writer to the annual meeting of the American Meteorological Society in Cambridge, Massachusetts (December 27, 1933), a progress-report was given outlining the methods used to obtain meteorological records under the extreme conditions experienced on Mount Washington [4]. The necessity of adapting standard low-level methods and instruments to the conditions on Mount Washington required considerable study and experiment.

The development of special devices to measure wind (Figs. 5, 6, and 7) and precipitation (Fig. 4), together with operating and experimental results, have been the subjects of separate papers [5,6,7]. The difficulties in the determination of relative humidity at low temperatures by means of ordinary methods suggested investigations of this important problem. Careful observations were made of optical phenomena [8] and aurorae.

The correct interpretation of Mount Washington observations is dependent, to a great extent, on the results of investigations by means of airplanes and kites to determine the influence of the mountain on the chief meteorological elements. A project undertaken many years ago was resumed on Mount Washington last summer by S. P. Fergusson of the Blue Hill Observatory of Harvard University, and discussions of the results were presented to the sections of Hydrology and of Meteorology of the American Geophysical Union at its meetings in April 1934 by him and Irving I. Schell [9 and 10].

Preliminary summaries of some of the elements have been made by the Observatory staff (A. A. McKenzie, S. Pagliuca, W. Stephenson, and R. G. Stone), and are given in condensed form in Table 1 and in Figures 9 to 12.

Table 1--Extremes recorded during November 18, 1932 to May 1, 1934, at Mount Washington, New Hampshire (elevation 6284 feet or 1915 meters)

Element	Value	Date	Value	Date
Temperature in °F	71	June 28, 1933	-46.5	Jan. 29, 1934
Greatest daily range in °F	64	January 29, 1934		
Pressure in inches	24.21	April 30, 1934	22.81	March 9, 1934
Wind-movement				
(a) 24 hours in miles	3095	From 4 p.m. April 11, 1934		
(b) 1 hour in miles	173	April 12, 1934		
Wind-velocity				
5-minute average in m/h	188	April 12, 1934		
Maximum gust (1/10 mile) in m/h	231	April 12, 1934		
Greatest precipitation during 24 hours in inches of rain	4.71	August 24, 1933		

Publication of the complete series of observations, tabulated according to recommendations from the Commission, is being carried on under the supervision of Dr. C. F. Brooks, Director of the Blue Hill Observatory. Photostat copies of the automatic records may be obtained.

The chief value of the Mount Washington observations is in connection with a three-dimensional study of special conditions, particularly when upper-air data are lacking. Thermograms obtained at the summit and at the two base-stations should prove helpful in determining (1) the time of front passages, (2) temperature lapse-rates, and (3) in general the vertical structure of air-masses in the particular region. This study requires considerable time and coordination of the various elements.

The summaries obtained so far are of climatological and general synoptic interest. They are also helpful in revising some of the normals obtained on Mount Washington by the United States Signal Service. The interest shown by leading meteorologists in the Mount Washington observations and the present tendencies towards developing observations on airplanes and on mountains in this country suggested the advisability of continuing the operation of the Observatory after the close of the Second International Polar Year.

At its inception the radio work at the Observatory was carried on primarily for communication with the base at Pinkham Notch. Although communication with Boston on the amateur 3.5-mc band was contemplated, the project did not prove feasible owing to frequent failure of the necessarily long and much-exposed antenna-systems. On the other hand, the very short antennas required for satisfactory operation on the amateur 56-mc band could be erected within the Observatory, away from wind and rime. It is on this latter frequency-band that radio-phone communication has been maintained with Pinkham Notch upwards of 19 months.

In December 1932 a voice circuit was opened between the mountain and an amateur station operated by Henry S. Shaw at Exeter, New Hampshire (91 miles distant), and considerably off the optical path, formerly supposed to be necessary for transmission on this high frequency. With improvements in terminal equipment (Fig. 8), this circuit has become increasingly reliable.

The spring of 1933 marked the beginning of ultra high-frequency radio communication between Mount Washington and the Blue Hill Observatory at Milton, Massachusetts. Although signals have been audible at all times, the strength has showed marked variation, rendering this 142.5 miles path least reliable of the three mentioned. Before the end of the Polar Year rough measurements of signal-strength were under way. The work is being continued with a minimum of 17 observations per day on the signals sent automatically at half past each hour from the Blue Hill Station. Greenleaf W. Pickard, of the General Radio Company, and Research Associ_te at the Blue Hill Observatory, is endeavoring to correlate signal-changes with meteorological factors.

The daily report from the summit is being included in the Commercial and Aviation Bulletin of the United States Weather Bureau, broadcast by Naval radio over NAA and NSS. It is also made available to the public daily at 9:55 a.m. Eastern Standard Time over WBZ.

A permanent observatory on the summit of Mount Washington equipped to fill the needs of modern synoptic meteorology and made available to students for the many research problems that can be conveniently investigated under very favorable field-conditions, would more than repay the modest expense involved. This fact is well appreciated by responsible heads of bureaus and institutions. What is needed for the immediate future is a coordination of efforts to prevent discontinuing the Mount Washington Observatory because of lack of funds.

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APPARATUS TO BE CARRIED ON THE NATIONAL GEOGRAPHIC SOCIETY—ARMY AIR CORPS STRATOSPHERE-FLIGHTS

Albert W. Stevens

(Abstract)

The proposed stratosphere-flight is sponsored by the National Geographic Society and the United States Army Air Corps. The first ascent may be made between June 15 and July 1, 1934; a second ascent may be possible in September or October. The point of departure will be somewhere east of the Rocky Mountains because of the probable direction of drift to the east and southeast.

The equipment, practically all specially designed, will be largely automatic, photographic records being obtained. Altitude will depend (1) on temperatures and pressures, the first by two photographically recording resistance-thermometers mounted outside the gondola and the second by photographic record of height of mercury column, and (2) upon photographs of the ground and of compass for direction taken at intervals of one and one-half minutes. For cosmic radiation, five instruments are being provided. Three of these are of the Millikan-Neher type, one of which is unshielded, one shielded with 180 pounds of lead-shot, and the third shielded with 600 pounds of lead-shot. Bursts of cosmic rays will be recorded by the use of an ionization-chamber, while Geiger counters will be depended upon for direction of rays, with photographs of compass to show orientation of apparatus.

Atmospheric conductivity and potential-gradient will be photographically recorded during the second flight by newly designed apparatus from the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and from the Bartol Research Foundation of the Franklin Institute, respectively. One spectrograph will be suspended 400 feet below the gondola and another will be mounted in the gondola at a quartz window; alternate exposures of 10 seconds and 10 minutes will be made continuously during the flight.

Air-samples will be obtained (1) in 14-inch glass spheres with glass cocks and mercury seals, and (2) in 12-inch flasks connected to a long copper manifold. Ozone will be determined by the spectrograph.

Broadcasting apparatus will be supplied by the National Broadcasting Company and will probably operate on a wave-length of 19 meters. On account of the radio operations, all motors will be shielded.

Apparatus will be driven by dry-batteries, with storage-batteries for low-voltage requirements.

The port-holes will be 3/8-inch glass, double-walled. Of the ten port-holes, one will be at the top and one at the bottom of the gondola, four between its equator and bottom, and four at 45° above its equator. The two man-holes 18 by 20 inches will be arranged with levers so that they may be pried open. The gondola will be closed at an altitude of about 15,000 feet and again opened on the descent at about 25,000 feet. About 6,600 pounds of lead-shot will be carried as ballast, 2,000 pounds of which will be reserved for use on the descent. Parachutes will be provided on batteries and other equipment which may be thrown away.

Oxygen will be carried in one flask and liquid air in another, the latter being used to build up inside pressure because of any loss developed through leaks. The balloon will be inflated to about 7-1/2 per cent of its capacity at the ground. The gas will have expanded to the capacity of the balloon at about 60,000 feet altitude. Beyond that height, dependence must be placed on dropping of ballast for increased altitude. At the ceiling, which it is believed may exceed 70,000 feet, there will be remaining 2,000 pounds of lead-ballast for use in controlling the descent.

Besides the sponsors above referred to, financial assistance has come from many individuals. The scientific apparatus and scientific counsel have been generously given by the United States Bureau of Standards, the United States Weather Bureau, the United States Coast and Geodetic Survey, the National Research Council, the Research

Laboratory of the Eastman Kodak Company, the Franklin Institute, the Carnegie Institution of Washington, and many other organizations and individuals.

U. S. Signal Corps,
Wright Field, Dayton, Ohio

A SHORT REPORT ON THE FIFTH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS, LISBON, PORTUGAL, SEPTEMBER 1933

J. A. Fleming, H. D. Harradon, and W. D. Lambert

The Fifth Assembly of the International Union of Geodesy and Geophysics was held at Lisbon, Portugal, September 17-25, 1933. The Association of Geodesy, with a longer program of reports and discussion than the other associations, began its meetings three days before the official opening of the Assembly, September 17.

The meeting was attended by 178 official delegates and guests; this number does not include the wives and friends accompanying the delegates and guests. Official delegates represented 21 of the 37 countries adhering to the Union as follows: Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, Finland, France, Great Britain, Greece, Italy, Japan, Morocco, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United States, Yugoslavia. Countries not yet adhering to the Union, represented by invited guests, were British India, China, Germany, and Venezuela. Thus the total number of countries represented at this Assembly was 25. The United States was represented by six delegates, namely, Walter D. Lambert, James B. Macelwane, S.J., Harry D. Harradon, John A. Fleming, and Thomas G. Thompson, who represented the National Academy of Sciences and the National Research Council, and David McD. LeBreton, who represented the Hydrographic Office of the United States Navy.

At the opening session President Lallemand paid homage to the memory of 41 geophysicists deceased since the Stockholm Assembly (1930); of these, ten were Americans.

The matter of greatest importance coming before the general assembly of the Union concerned a number of proposals of the Special Commission of Statutes and Finance. The resolutions resulting from these proposals and adopted by the Assembly were nine in number. Of these, the first four involved changes in the Statutes and therefore required two-thirds of the votes of the adhering countries; the remaining resolutions required only a majority of the votes of the countries present and voting. The resolutions referred to the following matters:

(1) National contributions--In the case of countries having large illiterate population, the Bureau was empowered to fix a contribution less than would be determined by actual population.

(2) Voting on administrative or mixed questions--In cases where questions of finance were not involved it was agreed that each country should have one vote, while in case of questions involving finance it was agreed that the number of votes per country should be allotted on the basis of the respective contributions.

(3) Financial year and payment of contributions--Action was taken that the financial year shall be the calendar year, the contributions for each year to be payable in the year in which due.

(4) Temporary reduction in dues--It was agreed that reduction of 25 per cent be effective in the contributions for each year until the next Assembly.

(5) Proposal made by the Italian National Committee--After considering the proposal of the Italian National Committee that statutes of the Union should be operative only after they have been submitted through diplomatic channels and have been ratified by the interested countries, the Secretary-General was directed to transmit the proposal to all organizations adhering to the Union who might then instruct their delegates to the next Assembly on this important matter.

(6) Form of accounts--It was agreed that, so far as possible, a uniform procedure in form of accounts be maintained for the Union and for the individual Associations.

(7 and 8) Arrangement of program of the general assemblies--Action was taken to the effect that future assemblies shall end before October 1 of the years in which held, and the Secretary-General was charged with calling the attention of

secretaries of associations to the desirability of arranging programs so that delegates may attend meetings of more than one Association.

(9) Overlapping of the activities of various international scientific organizations--The Executive Committee of the Union was instructed to investigate possible overlapping of the activities of various international scientific organizations dealing with the geophysical sciences and to submit suggestions to minimize any possible duplication, if found, in such matters.

For complete texts of the resolutions adopted and briefly abstracted in the following summaries of proceedings of the meetings of each Association, reference may be made to the account of the Lisbon Assembly published by the Secretary-General (Union Géodésique et Géophysique Internationale, Cinquième Assemblée Générale réunie à Lisbonne 17-25 septembre 1933; London and Southampton, Camelot Press, Ltd., 1934).

Since the Stockholm meeting in 1930, Australia, French Indo-China, and British India have withdrawn, and the French Protectorate of Tonkin has applied for admission with effect as from the year 1931-1932.

The officers elected at the Lisbon Assembly by the Union and its associations are listed in Table 1.

Table 1--Officers of the International Union of Geodesy and Geophysics and of its associations, 1933-1936 (except as otherwise indicated)

President--William Bowie
Vice-Presidents--Presidents of the Associations
Secretary-General--H. St. J. L. Winterbotham, Ordnance Survey Office, Southampton, England

Association	President	Vice-President	Secretary	Executive Committee
Geodesy	F. A. Vening Meinesz	E. Soler[2] G. Lenox-Conyngham	G. Perrier[2] [19, Rue Auber, Paris (9e), France]	I. Bonsdorff, C. F. Baeschlin, K. Weigel[1], and W. D. Lambert[1]
Seismology	E. Oddone	O. Somville H. Jeffreys	E. Rothé [38, Boulevard d'Anvers, Strasbourg, France]	F. M. da Costa Lobo, J. Galbis, N. H. Heck, A. Imamura, and J. Mihailovoc
Meteorology	A. Wallén	F. Eredia V. Bjerknes	Ph. Wehrlé [196, Rue de l'Université, Paris (7e), France]	- - - - - - - - - - -
Terrestrial Magnetism and Electricity	J. A. Fleming	V. Carlheim-Gyllensköld Ch. Maurain	D. la Cour [Toldbodvej 15, Copenhagen, Denmark]	J. Agostinho, A. Crichton Mitchell, S. Chapman, and C. Størmer
Physical Oceanography	M. Knudsen	E. Fichot	J. Proudman [The University, Liverpool (3), England]	O. de Buen, B. Helland-Hansen, G. Magrini, T. G. Thompson, E. Caballero y Lastres[1], L. Joubin[1], D. J. Matthews[1], and R. Witting[1]
Volcanology	C. Kténas	A. Michel-Lévy A. Machado e Costa H. Tanakadate	A. Malladra* F. Signore[3]	- - - - - - - - - - -
Scientific Hydrology	J. Smetana E. B. H. Wade[4]	O. Lütschg A. Narciso[4]	F. Diénert [26, Boulevard Jourdan, Paris (14e), France]	G. de Marchi, J. M. Torroja, P. H. Watier, and T. Zubrzycki

[1] For 1933-1939. [2] For 1933-1942. [3] Assistant Secretary. [4] Honorary.
*Address: R. Osservatorio Vesuviano, Resina (Napoli), Italy.

Association of Geodesy

Preceding the meetings of the Association of Geodesy were two meetings of its Executive Committee and a meeting of the Permanent Commission. Four of the seven members of the Executive Committee, including the President, Dr. William Bowie, were represented by proxy. The three members of the Committee in their own right were the Secretary, General Perrier of France, Professor Bonsdorff of Finland, and General Seligmann of Belgium. The last-named, being the senior member present, presided over the meetings of the Executive Committee and on the proposal of the Committee was designated as the presiding officer for the session of the Permanent Commission and for the general sessions of the Association.

The Executive Committee and the Permanent Commission spent much of the time in revising and polishing the draft statutes submitted by the Committee on Statutes, of which General Seligmann was chairman. The proposed statutes with final revisions from all sources were adopted at the first general meeting of the Association to take effect immediately. Some of the changes were: (1) Ineligibility of the president for immediate reelection; (2) addition of a second vice-president chosen from the country where the next regular meeting is to be held; (3) a compromise method of voting (a) by individuals on scientific matters, (b) by countries (each country having one vote) on administrative matters including elections, and (c) by countries (the number of votes increasing with the population) on matters involving finance.

In accordance with a resolution adopted at Stockholm the national reports were merely distributed; no time was allotted for even brief comments. The general reports were distributed with only a few brief remarks by each reporter.

Most of the work was done through the deliberations of the 17 commissions of the Association, the general reports having been previously presented to the commission or commissions most concerned. This practice, which seems to be a reasonable one under the circumstances, makes it necessary for a country to have more than one delegate, if it is interested in more than one aspect of Geodesy, for time is limited and committee meetings conflict. Thus the United States should have in future at least three representatives for Geodesy--indeed five would not be too many.

An idea of the more important matters engaging the attention of the Association may be obtained from the following brief summary of the resolutions presented to and adopted by the General Assembly:

(1) Gravimetric determinations in seismic regions should be intensified and, if possible, observations should be obtained in such regions by other geophysical and geological methods suitable for contributing to the investigation of the Earth's crust.

(2) The importance of the study of gravity and the form of the geoid in India as accomplished by the Survey of India was recognized by the Union, which regards as most desirable extension of similar work across Burma, Siam, Indo-China, and Malaya, to connect with the pendulum-work by Dr. Vening Meinesz in the waters surrounding the Dutch East Indies.

(3) The desirability of gravimetric observations in the waters between the Ganges Delta and Singapore as well as in the region of great ocean-deeps to the east of the Philippines and Japan was recommended.

(4) Adhering governments were recommended to furnish to geodesists the means requisite for making gravimetric determinations on land and sea in the Southern Hemisphere, where such determinations are almost wholly lacking.

(5) Following the proposal of the associations of Geodesy, Seismology, Volcanology, and Physical Oceanography, the Union expressed the desire that there be established temporary gravimetric stations suitably equipped with instruments for measuring the variations from the vertical to investigate (a) general continental displacements along a line across a continent (preferably North America), (b) regional movements at various points from 200 to 300 km apart, (c) tides in the open sea along a line of isolated islands, and (d) more especially tides in seismic regions. [This resolution was adopted on the joint recommendation of the four associations meeting in joint ses-

sion after hearing a lecture by Professor Tomaschek of Marburg, Germany. The resolution as it stands needs the background of Professor Tomaschek's work and lecture and the report on earth-tides previously presented to the Association. Professor Tomaschek has devised a remarkably accurate method for determining variations in gravity with time, that is, variations principally due, as far as we know, to the tidal effects, direct and indirect, of the Sun and Moon. The results are of great interest to all the associations supporting the resolutions, and the value of the observations would increase rapidly with an increase in the number and variety of the places where the observations would be made.]

(6) The Union reaffirmed the resolution adopted at Stockholm in 1930 with reference to the 30th meridional arc in Africa, calling attention of the governments concerned to the need of completing this arc and of undertaking the measurement of two arcs of parallel, one near the equator from Senegal to Somaliland and the other along the parallel of 6° south latitude.

(7) The Union urged action to obtain prolongation of the meridional arc from the Arctic Ocean to the Mediterranean and to the Cape of Good Hope, suggesting steps be taken asking Turkey to adhere to the Union in view of the sector of this arc in Turkey between triangulations of Bulgaria and Syria.

(8) The governments of India and Siam were congratulated upon completion of triangulation-connections between India and Siam and it was recommended that steps should be taken to complete the important geodetic connections between Malaya and Sumatra, Siam and Malaya, Burma and French Indo-China, and to the eastward of existing triangulation in Dutch East Indies.

(9) The Union agreed to provide a regular annual subvention within its means to the Bureau International de l'Heure. The desire was expressed that there be formed a mixed joint commission named partly from the International Union of Geodesy and Geophysics and partly from the International Astronomical Union to take charge of the work of international longitude-operations, to be a commission analogous to the joint Commission on the Variation of Latitude.

(10) The Union expressed the desire that submarine gravimetric operations be extended by Italy and by France in the Mediterranean.

(11) All geodetic services were recommended to calculate their first-order triangulations on the International Ellipsoid of Reference adopted at Madrid in 1924, using the international formula for normal gravity-intensity adopted at Stockholm in 1930.

(12) The Union expressed the opinion that the Association of Geodesy should prepare a publication discussing the values of gravity at the base-stations of the different nations. [It might seem as if this were a matter chiefly of interest to geodesists, so that there was need of referring the matter to the Union. However, the values of gravity are so important in branches of geophysics other than geodesy, that it is desirable to systematize our present knowledge and to supply deficiencies, and the resolution is thus properly a Union matter.]

Various subjects were of course considered in committee and were the subjects of resolutions or votes in the committee, but were not submitted to the Association for action. Not all of these can be mentioned. This is because there was only one representative of the United States for Geodesy, who could not "cover" all the committee meetings. The official reports, when published in the "Bulletin Géodésique," will doubtless give all required information. Of those not already indicated by resolutions adopted, the following may be selected for mention.

The Commission on Bibliography reported that the International Bibliography of Geodesy covering the years 1928, 1929, and 1930 will soon be in press; it is expected that a new volume will appear every three years.

The Commission on Projections requested the National Committee on Geodesy in each country to consult with those most interested in each country in the endeavor to provide the most satisfactory maps possible for aerial navigation.

The mixed Commission on the Variation of Latitude heard with regret that its Chairman, Dr. H. Kimura, felt that because of the infirmities of age he would soon be obliged to resign. The Commission considered the measures to be taken in the event of his resignation to ensure the continued smooth working of the International Latitude Service but took no definite action, feeling that final action could be postponed till the meeting of the Astronomical Union in 1935.

The Commission on the Adjustment of European Triangulation on a common datum, after discussing the objections that had been raised against the underlying idea, decided that the adjustment in question is desirable and voted to accumulate data for the use of a sub-committee that would study the best method of effecting the adjustment.

In addition to the lecture of Professor Tomaschek already mentioned, there were lectures by Dr. Vening Meinesz on the interpretation of his determinations of gravity and by Professor Holweck on the Holweck-Lejay gravity-apparatus, and the results obtained with it.

Besides reference to the Secretary-General's printed report of the Assembly, above noted, reference may be made to General Perrier's account given in the Annuaire du Bureau des Longitudes for 1934, and to the brief notice by "A.R.H." in the Geographical Journal (London) for November 1933; the latter, while covering the whole meeting, emphasizes Geodesy.

Association of Seismology

During the first sessions of the International Association of Seismology, considerable time was consumed in the discussion of financial matters.

The Association took under consideration a large number of general matters such as the definitive adoption of the telegraphic code, and the question of its notations; a report was heard on hodochronic curves and a commission was appointed to care for the publication of new tables.

The status and needs of the "International Seismological Summary" were presented, from which it developed that an annual appropriation of about 60,000 French francs, or double the amount previously contributed, would be required if publication were to be continued, and a resolution was passed recommending to the Union that not only should the small budget of the Association not be decreased but that an additional 30,000 francs be granted yearly to the "International Seismological Summary" to enable continuance of that publication.

From the large number of reports on the state of seismology in the various countries, it is not surprising that, in the present financial crisis, many ended with the request that the Association recommend that their respective governments make more liberal appropriations for seismological investigations. A resolution to that effect was adopted by the Association.

Following the Secretary's comprehensive report on his correspondence in regard to the publication of tables of travel-times, it was moved and carried that the new tables by Jeffreys be printed by the Association. It was, however, deemed desirable that the Association should publish several tables and thus make them available. A new committee was appointed to select tables for publication by the Association.

Association of Meteorology

In the meetings of the Association of Meteorology, under the presidency of Dr. A. Wallén, 14 scientific communications were presented relating chiefly to the following subjects: (1) Value of applying to forecasting modern theoretical ideas on the mechanics of the atmosphere; (2) theories and observations on the formation of clouds and precipitation; (3) ideas and theories of the general circulation of the atmosphere, particularly with reference to transformations of energy; and (4) geophysical knowledge of the stratosphere.

The principal subvention made by the Association was that of 100,000 French francs, accorded the International Polar Year Commission towards the publication of the results of that important enterprise. The Commission on the relations of the Association with the International Meteorological Organization pertaining to the Second International Polar Year was continued.

Upon the Association's recommendation, the Assembly adopted the following resolution:

> "The International Union of Geodesy and Geophysics, in consideration of the importance of the work of the Apia Observatory (Samoa), not only as regards measurements at the Earth's surface but also the soundings of the upper atmosphere, regarding which so little is known in these latitudes, expresses the desire that the Observatory's work be continued without any reduction of the material means placed at its disposal."

A resolution was passed by the Association adopting certain principles to be followed in granting subventions. These are as follows:

(a) Subventions may be granted for aid in collecting, discussing, and publishing observations already made in different countries and for the assembling of which international collaboration is requisite.

(b) Subventions may be granted for facilitating the organization of investigations in several countries, but subventions for the purchase of instruments--to remain the property of the Association--for approved researches, may be granted only if it is necessary to use simultaneously the same model in several countries, and no subvention may be made for investigations in a single country.

(c) Subventions may be granted for facilitating the comparison of instruments with a model in use in another country, but such subventions can cover only costs of transport and travel and may not be granted for the construction and perfection of a standard.

(d) The President is authorized to publish certain exceptionally important memoirs, the publication of which would ordinarily be difficult; he should, however, before doing so, obtain the advice of specialists, not belonging to the nationality of the author.

The Association was of the opinion that the system of work adopted for the Lisbon Assembly should be continued for future meetings. The subjects for discussion should be circulated at least a year before the meeting; communications to be presented should be distributed at least two months before the meeting, and if of a mathematical nature, in their entire text, with complete bibliographical references. In order that the memoirs may be printed in time, they should reach the Secretariat at least five months before the meeting before which they are to be presented.

The Association also adopted resolutions expressing thanks to the Government of Czechoslovakia for its contribution to actinometric research by facilitating the work of F. Volochine, at the Observatory of Trappes, and to the Director of the National Meteorological Office of France for the financial and material support accorded the International Actinometric Bibliography.

Association of Terrestrial Magnetism and Electricity

The five sessions of the Association of Terrestrial Magnetism and Electricity, under the presidency of Dr. J. A. Fleming, were attended by representatives of 14 countries.

The Association evinced its interest in many geophysical researches now in progress, among which may be mentioned the continuous observations of solar phenomena which may lead to the production of certain phenomena in the upper atmosphere, the results of spectrohelioscopic observations now being obtained at widely distributed points on the Earth's surface, the international aspects of cosmic-ray research and particularly the desirability of equipping selected permanent stations with apparatus for continuous photographic registration of cosmic radiation, observations pertaining to lightning and the aurora, and a number of technical matters regarding publication.

The reports of the Sub-committee on the Second International Polar Year indicated that highly satisfactory work had been accomplished and that data of inestimable value to geophysical researches had been collected. The Association decided to assist financially as much as possible in the editing and publishing of the results and to continue the Sub-committee on the Polar Year, particularly for assuring the proper distribution of instrumental equipment constructed for Polar-Year work.

One of the principal matters engaging the attention of the Association was the improvement of the present unsatisfactory distribution of magnetic and electric observatories, through the continuation of existing, and the establishment of new, observatories at suitable points. The sense of the Association was contained in a series of resolutions expressing satisfaction to some governments for the continuation of certain observatories and urging others to establish new ones at selected sites. Consideration was also given to the difficult question of division of observatory-work, particularly in Europe.

Recognizing the importance of obtaining observations at repeat-stations for the study of the secular variation, the Association adopted a program of work based on the exigencies of recent research and embodied in a report prepared by its Special Committee on Secular Variation, as a minimum requirement and expressed the hope that governments would take steps to secure secular-variation data not only in their own geographic limits but also in their colonies.

A good notion of the work accomplished at the meeting may be obtained from perusing the 23 resolutions passed by the Association, an English translation of which occurs in the Journal of Terrestrial Magnetism and Atmospheric Electricity (v. 38, pp. 317-322, 1933).

Association of Physical Oceanography

The Association of Physical Oceanography held four sessions under the presidency of Professor M. Knudsen. The statutes of the Association which had been drafted by the Executive Committee and circulated during October 1933 among the national oceanographical committees, and other national representatives of the Union, were adopted after a few amendments had been made.

Reports were received from (1) the Secretary, on the work of the Association and its finances, (2) the representatives of the Association to the Hydrographic Conference at Monaco, (3) the Secretary of the Commission on Tides, and (4) the Secretary of the "Commission pour l'étude des raz de marée."

Considerable attention was given to the proposal of a second edition of the General Bathymetric Chart of the Oceans, resulting in the approval of the following official statement:

> "The International Association of Physical Oceanography expresses its appreciation of the efforts which are being made by the International Hydrographic Bureau towards the publication of a revised edition of the Carte bathymétrique générale des Océans. It declares its sense of the value which such publication would render to the Science of Oceanography and hopes that the publication will not be unduly delayed by lack of financial resources."

Among the nine papers presented before the Association was one read by Captain D. McD. LeBreton on "Bathymetry and water-circulation of the North Pacific Ocean, and gravity-investigations of the West Indies Region" by the United States Hydrographic Office, and one by Professor T. G. Thompson "On the organization of United States oceanographical research on the Pacific Coast of the American Continent, and on the work of the University of Washington, Seattle."

As a result of the discussion of the mean sea-level and its changes, it was agreed to appoint a Commission on this subject and to ask for the collaboration of the Association of Geodesy and of the International Hydrographic Bureau of Monaco.

One meeting was largely devoted to consideration of the report of the Commission on Tides, in which it was agreed to pass a resolution recording the Commission's appreciation of the active cooperation of the International Hydrographic Bureau in collecting and publishing information relating to existing records of observation of sea-level and to national tidal services.

Association of Volcanology

Among the scientific studies of active and extinct volcanoes and volcanic phenomena in general communicated to the Association of Volcanology, there were (1) investigations of the activity of Vesuvius and associated seismic and meteorological phenomena, (2) volcanic and geophysical phenomena of the Azores, (3) the eruption of 1931 at La Réunion, the eruption of 1929 at Martinique, and the volcanic formations of the primary epoch in Anatolia, (4) investigations of the alkaline volcanoes of the Pliocene in the southern group of Antiparos (Archipelago), and (5) investigation of the italitic rocks of Somma-Vesuvio.

On the proposal of the Dutch National Committee, the Association gave its approval to the formation of a mixed commission of members from the associations of Geodesy, Volcanology, and Physical Oceanography for the study of the Earth's crust in general.

On the proposal of the American Geophysical Union, the following resolution was recommended to, and adopted by, the General Assembly:

> "The International Union of Geodesy and Geophysics expresses the desire that governments and private organizations of regions in which there are unexplored or insufficiently explored active volcanoes, organize expeditions for the purpose of collecting useful data on these volcanoes. Appeal is especially made in this connection to Kamchatka and the French Colonies where active volcanoes exist."

Association of Scientific Hydrology

The Association of Scientific Hydrology held five meetings, devoting attention largely to questions pertaining to potamology, limnology, subterranean hydrology, glaciology, statistics, and practical applications. No definitive action could be taken because further study is required. It developed that certain questions should be extended, and accordingly the nine following items were included in the Agenda for the next meeting of the Association: (1) Measurement of evaporation, apparatus, critical discussion of results obtained; (2) influence of forests on liquid and solid discharge of water-courses (recent and current investigations, methods used); (3) determination of the solid discharge of water-courses (recent investigations and results); (4) correlative measurements of temperatures and currents in natural and artificial lakes and descriptions of methods and apparatus used; (5) definition of the different underground-waters; (6) study of the circulation of waters in the portion of the ground between its surface and the underground water-level; (7) variation of glaciers and gaging the ablations thereof; (8) classification of water-courses based on statistical methods; (9) methods of gaging discharge, particularly in the existing installations with reference to motive force and irrigation.

The Association decided to establish a seventh Commission to be known as the Commission on Snow.

The two following resolutions were recommended to, and adopted by, the General Assembly of the Union:

> "(1) The International Union of Geodesy and Geophysics, considering that there is frequently found in geophysical and technical publications erroneous or even contradictory information on the discharge of various water-courses, expresses the desire that all countries, whether adhering or not to the Union, establish tables giving the mean annual discharge or possibly the other characteristic discharges of the principal rivers of the world (indicating the periods of observations)."

> "(2) The International Union of Geodesy and Geophysics, noting the ever-increasing scientific and practical importance of the study of underground water, expresses the desire that, in all countries, whether adhering or not to the Union,

there be established organizations for hydrological research and that there be made available to them as soon as possible all the material and personnel required for the pursuit of these investigations.

Department of Terrestrial Magnetism, Carnegie Institution of Washington (J.A.F. and H.D.H.),
U. S. Coast and Geodetic Survey (W.D.L.),
Washington, D. C.

RESOLUTIONS ADOPTED

(I) RESOLUTION ON THE DEATH OF HENRY STEPHENS WASHINGTON

WHEREAS, In the death of Henry Stephens Washington on January 7, 1934, the American Geophysical Union lost one of its original members, who served successively as Chairman of the Section of Volcanology, Chairman of the Section of Geophysical Chemistry, and Vice-Chairman and Chairman of the Union, and

WHEREAS, Dr. Washington made notable contributions in the fields of geology, mineralogy, and volcanology, particularly in the chemical analysis of rocks, the classification of igneous rocks and studies as to their relation to volcanic activity, and the constitution of the interior of the Earth, therefore be it

RESOLVED, That the American Geophysical Union records this expression of its sense of great loss in his death, and be it further

RESOLVED, That a copy of this resolution be sent to Dr. Washington's family, to the President of the Carnegie Institution of Washington, and to the Director of the Geophysical Laboratory.

(II) RESOLUTION ON AURORAL OBSERVATIONS AT COLLEGE, ALASKA

(Proposed by the Section of Terrestrial Magnetism and Electricity)

WHEREAS, On November 8, 1929, the Rockefeller Foundation appropriated the sum of $10,000 to establish, equip, and maintain a first-order auroral station at College near Fairbanks, Alaska, to carry out a five-year program of research on the aurora, and

WHEREAS, This work has been carried out successfully since 1930 under the efficient direction of Professor Veryl R. Fuller of the Alaska Agricultural College and School of Mines, is giving results of great value in the systematic study of auroras, and constituted an important link in the chain of Polar Year stations, and

WHEREAS, This station is in a particularly desirable location, not only from the favorable surroundings, but because it is practically 180° distant in longitude from the first-order station in Norway, therefore be it

RESOLVED, That the American Geophysical Union expresses the hope that means will be found to continue the operation of this station beyond the five-year period for which provision was made, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the Alaska Agricultural College and School of Mines and to the Rockefeller Foundation.

(III) RESOLUTION ON THE DEATH OF WILLIAM MORRIS DAVIS

(Proposed by the Section of Oceanography)

WHEREAS, In the course of a long and distinguished career, William Morris Davis made notable contributions to oceanography as well as to meteorology and the explanation and classification of land forms, and

WHEREAS, In particular, he brilliantly analyzed the evidence presented by coral reefs as to Pleistocene and recent changes in sea-level, therefore be it

RESOLVED, That the American Geophysical Union expresses its deep regret at the death of Professor Davis on February 5, 1934, and honors the memory of one who so greatly advanced human understanding of the oceans, the atmosphere, and the forms of the Earth's surface, and be it further

RESOLVED, That a copy of this resolution be sent to Mrs. Davis, to the President of Harvard University, and to the Chairman of the Administrative Board of the California Institute of Technology.

(IV) RESOLUTION REGARDING CARTE BATHYMÉTRIQUE GÉNÉRALE DES OCÉANS

(Proposed by the Section of Oceanography)

RESOLVED, That the American Geophysical Union expresses its appreciation of the efforts which are being made by the International Hydrographic Bureau towards the publication of a revised edition of the Carte Bathymétrique Génerale des Océans, declares its sense of the value which such publication would render to the science of Oceanography, and hopes that the publication will not be unduly delayed by lack of financial resources, and be it further

RESOLVED, That a copy of this resolution be sent to the International Hydrographic Bureau.

(V) RESOLUTION ON THE DEATH OF FRED FORBES HENSHAW

(Proposed by the Section of Hydrology)

WHEREAS, In the death of Fred Forbes Henshaw on December 26, 1933, the American Geophysical Union has lost a member who has long been active in hydrologic studies, and

WHEREAS, He has contributed largely to the observations and interpretations of hydrologic phenomena and to the literature of hydrology and hydraulics, therefore be it

RESOLVED, That the American Geophysical Union expresses its sense of great loss through his death, and be it further

RESOLVED, That a copy of this resolution be sent to Mr. Henshaw's family.

(VI) RESOLUTION ON THE DEATH OF FLOYD AUGUST NAGLER

(Proposed by the Section of Hydrology)

WHEREAS, By the death of Floyd August Nagler on November 10, 1933, the American Geophysical Union has lost one of its most active and productive workers in the field of experimental hydraulics, and

WHEREAS, He rendered outstanding service in the upbuilding of the hydraulic laboratory at the University of Iowa and in promoting research in the fields of hydrology and hydraulics, therefore be it

RESOLVED, That the American Geophysical Union expresses its sense of great loss through his death, and be it further

RESOLVED, That copies of this resolution be sent to Professor Nagler's family and to the President of the University of Iowa.

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF GEODESY

Washington, D. C.
April 26, 1934

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PLANE COORDINATE-SYSTEMS FOR INDIVIDUAL STATES

Oscar S. Adams

The first-order control system of the United States established by the Coast and Geodetic Survey forms a very extensive unified framework for the country. There are already in existence some 40,000 miles of arcs of triangulation covering the country and cutting it up into a more or less regular checker-board arrangement. Plans have been made for a rapid extension of this control so as to place any point within easy reach of stations that can be used for local control.

These control-data should be a great asset to local engineers and surveyors, but too often it is entirely overlooked when work is undertaken on local and regional engineering projects. This condition is partly explained by the fact that heretofore all the data of this control have been expressed in geodetic form, that is, in the latitudes and longitudes of the stations and in the lengths and azimuths of the lines joining the stations. For those familiar with geodetic computations this is sufficient for the purpose. Unfortunately, geodetic computations are rather complicated and those not versed in them are inclined to shy at the very mention of such matters. We feel that this feeling is in large measure unjustified, but arguments have small weight when opposed to prejudice or to preconceived feeling.

It is true that cadastral and local surveys are in general confined to limited regions; hence it is possible to neglect the curvature of the Earth, and to make computations in the plane with accuracy sufficient for the purpose in hand. Of course, it is well known that no part of the Earth's surface can be represented on a plane with perfect accuracy, but often perfect accuracy is not essential for the work in progress. With this fact in mind, engineers and surveyors have long been in the habit of computing local projects by independent systems of plane coordinates established for the particular region or project. Thus each such survey forms a detached unit, and no control is applied to the work except the local checks furnished by the direct observations in the work itself.

This is probably satisfactory for very restricted undertakings, but when it is desired to extend the work farther and farther, difficulties and discrepancies are encountered until finally the whole has to be given up and a separate system established. Also, whenever two separate neighboring systems expand enough to overlap, very serious difficulties arise. Of course, it is possible even with the local systems to make some use of the control-data, but too often they are overlooked by those in charge of the work.

In view of the facts that have been enumerated, a demand arose among engineers and surveyors for systems of plane coordinates that would permit computations to be based on the regional control-system and at the same time to entail no more complicated computations than are encountered in the local systems of plane coordinates. It was also desired that these systems of coordinates should be as extensive as possible, so that rather large regions could be included in public-works surveys, public-roads surveys, and others of like nature.

A quite extensive study was made of the question by myself and others in the Coast and Geodetic Survey, and also by Colonel Birdseye and by members of the Geological Survey. It was finally decided to compute tables for plane coordinates for whole states wherever possible, or for specified sections of the states wherever the state as a whole was too large for a single system. It was felt that a great deal of local surveying and engineering work would be confined to the limits of the various states and that this plan would be applicable to all such work.

It was decided from our study that these plane coordinate-systems should be based upon one of the conformal projections. This type of projection preserves the angles in the plane, and hence there is less trouble to be encountered in azimuth-control. The Lambert conformal conic projection with two standard parallels was adopted for states with greatest extent in an east and west direction, and the transverse Mercator projection for states with greatest extent in a north and south direction.

The first request came from the Public Works Administration of North Carolina.

The Coast and Geodetic Survey in cooperation with this State was just completing a system of arcs of first-order triangulation in the State that forms one of the most extensive control-surveys of any state in the Union. After a preliminary study, we found that it was possible to devise a single system for the State within the limits of scale-variation that the Administration's officers said was allowable. This system was computed for them, and it has been in successful use in their operations now for some time. The plane coordinates are being computed for all of the triangulation-stations in the State so that all of the control-data will thus be placed on the grid. Engineers and surveyors can hereafter make use of these coordinates as control for their work and all necessary computations can be made on the plane in the way that is familiar to all.

The subject of plane coordinates is merely a particular application of the subject of general projections. In North Carolina the Lambert conformal conic projection with two standard parallels was used as a basis for the system. This scheme holds the scale exact along two standard parallels. Between these parallels the scale is too small and outside of them the scale is too large. The scale at a point is the same in all directions for infinitesimal distances which is a characteristic of all conformal projections. The scale along any given parallel is constant, but it varies from parallel to parallel.

The greatest variation in scale in North Carolina is one part in 6,000 which is less than a foot in a mile. These scale-variations are given in a table for the State for every minute of latitude so they can be taken into account in the computations. This is being done in the computations made by the State officials, and the results are very gratifying. The officials in that State are very active in this line of work at the present time under the relief appropriation. Those in charge of the work are very enthusiastic in their praise of the system as applied to their local surveys.

A computation for a similar system was made for Long Island, N. Y. Owing to the limited extent in latitude we were able to keep the scale-variations smaller than one part in 100,000 for the Island proper with most of it as good as one part in 200,000. This is well within the accuracy even of geodetic work, so it will not be necessary to trouble any about the scale-variation in using the system unless the most extreme accuracy is desired. This system is based on the same projection as was used in North Carolina. The cities of Brooklyn and New York could use this system to great advantage in the surveys within their limits.

As an example of what could be done in a state with greatest extent in a north and south direction, and with limited extent in an east and west direction, a study was made of the State of New Jersey. It was found that a transverse Mercator projection could be applied to that State with very satisfactory results. A transverse Mercator projection is the well-known Mercator projection with its axis turned in an east and west direction. As a result of this, it is related to a central meridian in the same way that the ordinary Mercator projection is related to the Equator. The scale is constant along this central meridian and along small circles parallel to this central meridian. We can conceive of the ordinary Mercator as mapped on a tangent cylinder and then this cylinder turned through an angle of 90° about an axis in the plane of the Equator until the Equator coincides with a meridian. If now we conceive of the parallels carried with the Equator, we shall have some idea of the new condition.

In order to get a balance of scale a certain reduction is made along the central meridian. The result of this is that the scale along two small circles a certain number of miles from the central meridian is held exact. For New Jersey the scale at the center was reduced one part in 40,000. The two circles of exact scale are approximately 28 miles east and west of the central meridian. With this scheme the variation in no part of the State is worse than one part in 20,000 and in most of it, it is as good as, if not better than, one part in 40,000. Now good second-order surveying is supposed to check as well as, if not better than, one part in 10,000, so the error of this system is well within the accidental error of such surveying as will be computed by means of the grid.

In this scheme the errors vary in an east and west direction, as opposed to the variation of errors in a north and south direction in the Lambert system. These errors of scale are given in the table for distances every 5,000 feet from the central meridian, so that they can be taken into account for very exact computations. I should be inclined to use them for any calculations, for the method is so simple that it can be applied by anyone using the grid.

Under the program of the Civil Works Administration the computation of tables for the states was expedited, and now the last state has been furnished with its appropriate tables. In case more than one system for a state was needed, the division between systems was made along county boundaries so that in all cases any given county lies entirely in one system. Iowa and Ohio required two systems each; Florida, three systems; Texas, five; and California, six. Thus every state in the Union is now provided with this aid to more accurate computation and control of local and regional surveys.

As already stated, the intent is to compute the _x_- and _y_-coordinates of all triangulation-stations on an appropriate grid within each of the states. Grid-azimuths will also be computed for objects that are visible from the ground at each station. In general, grid-azimuths on the main triangulation-stations are of little value to the local surveyor for the stations are frequently so far apart that they are not intervisible without the use of high towers. In all new triangulation, azimuth-marks are being set near the stations from a quarter of a mile to a mile distant. A grid-azimuth on this mark is all that is needed since a traverse survey could be started from the station by turning off the angle from this mark. It can be seen that only one grid-azimuth at a station is needed. Grid-azimuths between two stations for each of which the grid-coordinates have been computed can be found from these coordinates in the usual way. Between two intervisible stations a traverse could be run starting and ending on a given line.

In this short discussion I have not been able to do more than give you a general outline of what is being done, and to give you a brief indication of the advantages to be gained by the use of plane coordinates. "The proof of the pudding is in the eating," and the fact that this scheme has met with enthusiastic welcome in those states where it is being tried convinces us that we are thus taking an important step towards more accurate local and regional surveying as well as doing our part in simplifying the necessary computations. The actual use of the grid is the same in either the Lambert or transverse Mercator systems, the only difference being in the direction of the scale-variation. The reduction of geographic positions to grid-coordinates is by a different formula in the two systems, but after these coordinates are once computed, their further use is the same in both systems.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GRADUATION AND CALIBRATION OF PRECISION-CIRCLES

Lewis V. Judson

(Publication approved by the Director of the Bureau of
Standards of the United States Department of Commerce)

At the annual meeting of the American Geophysical Union in 1932 I reported on some tests made on the Bureau of Standards circular dividing-engine which demonstrated the high accuracy of that instrument. I am now prepared to give some results of a series of circles graduated on this engine for the United States Coast and Geodetic Survey.

These circles, intended for use in the 9-inch Parkhurst first-order theodolite, have been made of cast sterling silver. The choice of material was made by the United States Coast and Geodetic Survey. These circles are now being made under an arrangement whereby the entire task from the casting of the silver to the completion of the graduated circle is carried out at this Bureau.

The circles go through the following processes: (1) Casting of the sterling-silver disc; (2) heat-treatment to relieve the casting strains; (3) machining to approximate size; (4) heat-treatment to relieve machining strains and to further stabilize the material; (5) machining to a size suitable for plating; (6) electroplating with silver, using cyanide bath; (7) machining to finished size; (8) inscribing the coarse series of numbers and graduations; (9) polishing to a plane on pitch-lap with chromium oxide; (10) inscribing the fine numbers; (11) polishing the burrs from the fine numbers; (12) graduating the circle; (13) polishing the burrs from the graduation-lines; and (14) filling the lines with special black ink.

The heat-treatments are those advocated by the Metallurgy Division of the Bureau. The distortion of circles in the past is believed to be one cause for what have been called incorrectly-graduated circles.

The silver-plating was found necessary because it was not possible to graduate the sterling-silver discs and obtain the kind of graduation-line we knew it was possible to obtain, for example, on rolled sterling silver. The crystals of the sterling silver are large, and differ in physical characteristics even in a single circle so that the graduating tool will not cut uniform lines all around the circle. Many of the lines made on the sterling-silver crystals seem to be torn rather than cut.

The polishing of the circle is an essential part of our present procedure. This is not done for the purpose of getting a reflecting surface but for the purpose of getting a really plane surface for two reasons, first because the accuracy required demands it and secondly because lines with smooth, sharp edges can be made only under these conditions.

In the actual graduating of the circles we have made several changes and improvements, perhaps the most important of which is that of using a specially constructed diamond-point, adjusted so that a very fine shaving is cut out of the material, leaving sharp edges to the line and a very small amount of burr which is quickly removed with a pitch-lap and chromium oxide. No charcoal is used in our process at any time. The details of the method of graduating while interesting and of great importance are technical matters which are not appropriately discussed at these meetings.

Although several changes in the ruling mechanism of the dividing-engine were found necessary, the principal elements of the machine, the main central bearing, the worm, the gear-teeth around the periphery of the central table, and the contour of the correcting-device were found to be satisfactory.

After the circles have been completed they are checked up on our circle-testing machine. Because of the limited time we cannot make anything like a complete test of the circle, but with the microscopes set 90° apart we can make a rather good check to determine whether or not the graduations are uniformly spaced.

The Coast and Geodetic Survey then makes a more extended test of the circles when actually mounted in a theodolite. A series of collimators set up around a room with the theodolite in the center enables a series of measurements to be made just as they would be in the field, sighting many miles away. The results obtained in these tests agree with those made by this Bureau within the range of experimental error.

There is considerable difficulty in stating precisely how accurate these circles are. When it is considered that there are 4,320 lines on each of these circles and that on these 9-inch circles an angle of one second is about 0.00002 inch one must have considerable numerical data to support any statement made. These circles certainly are accurate within the tolerance of two seconds of arc given in the specifications. I believe that they may be within approximately ±1 second.

The research work on materials for precision-circles to which I referred in 1932 is being continued.

The successful carrying out of this program of preparation, graduation, and calibration of precision-circles at the Bureau of Standards has involved the fullest coöperation of several technical divisions of the Bureau, particularly the divisions of Metallurgy, Chemistry, Optics, and Weights and Measures. Credit for the actual graduation of the circles should be given to B. L. Page of the Division of Weights and Measures.

U. S. Bureau of Standards,
Washington, D. C.

LONGITUDE-DETERMINATIONS AT HONOLULU AS PART OF THE INTERNATIONAL PROGRAM OF 1933

J. P. Lushene

One who examines a map of the opposite coasts of the South Atlantic Ocean will be struck at the similarity of the shapes of the coast-line. Each major indentation on the east coast of South America has a corresponding protuberance on the west coast of Africa. If one were to take a compass and make measurements on a globe it would be found that dimensions agree closely.

A study of this phenomenon has brought about a new conception of the nature of the Earth's crust and movements or drifts of land-masses. This new conception is called the theory of displacement of continents or sometimes referred to as the displacement-theory.

One great advantage of this theory is that its early solution is possible by accurate astronomical determinations. In the years 1823, 1870, and 1907, observations were made on Greenland and disclosed an increase of longitude between Greenland and Europe amounting to an average of 18 meters per year for the 84 years. These results were obtained from a series of determinations of longitude by observations of the Moon's apparent position relatively to the stars. In most cases the results are not accepted due to the unreliability of the lunar method of longitude-determination.

Differences of longitude between Greenwich and Cambridge, Massachusetts, by means of cable signals were made in 1872, 1892, and 1914. The difference changed 0.016 second and 0.007 second, or a total of 0.023 second for the period. The problem of error was again brought up as cable signals are subject from time to time to disturbing influences, the true nature of which is uncertain, and these effects probably have a variation much greater than the small difference in question.

However, with the present-day radio and the creation of a world-wide network of longitude-stations with differences of longitude determined simultaneously at the various stations, the subject of uncertainties is largely eliminated. The first campaign of the world-longitude program was carried out in 1926. During the months of October and November 1933 the second campaign was carried out. The observations at Honolulu were undertaken by the Coast and Geodetic Survey.

The station at Hawaii is seven miles southeast of the city of Honolulu. The site was selected principally for its clear atmosphere and excellent radio reception. As the Observatory was temporary for use during October and November only, the question of providing an accurate timepiece was a problem. No astronomical clock was available and even though a clock could be obtained it would have been impracticable to construct the necessary vaults for constant temperature and pressure. The problem was solved in 1926 by Dr. Bowie, who suggested the use of our standard gravity-pendulum as a timepiece. The pendulum, a quarter-meter, half-second pendulum, was swung in an air-tight receiver in a partial vacuum and gave excellent time-control.

Every 24 hours the short-wave signal from Arlington was recorded and this marked the beginning and end of the respective swings. The corrections for the time-signal used was determined by the United States Naval Observatory. In this manner the daily period of the pendulum was determined. For the longitude-work, long-wave signals from Annapolis, Honolulu, Saigon, Tokio, and Malabar were received and the short waves from Tokio, Saigon, and Arlington. These signals were recorded on the chronograph in the customary procedure. Whenever a time-signal or star-transit was recorded on the chronograph a comparison was made with the free-swinging pendulum. The comparison was made by the method of coincidences using a neon tube, operated by a thyratron-tube amplifier connected to the master-chronometer. The coincidences were very regular and uniform and an excellent comparison was made. With the period of the pendulum for the day determined accurately, as stated previously, computations can easily be made to check the rate of the chronometer over the interval between the mean epoch of the time-observations and the time of the radio signals. If the temperature and pressure were kept uniform, the pendulum maintained a very constant rate and constituted an excellent timepiece. The pendulum was kept swinging continuously during the two months of longitude-observations, and many radio signals that could not have been used otherwise were thus connected with the local time-observations.

The long-wave signals from Saigon, Tokio, and Malabar were received with great ease at the hours of 12:30 a.m., 1:30 a.m., and 2:00 a.m., respectively, Honolulu standard time. This close group of signals made this particular time of the night an excellent period for star-observations. Four stars were observed before and after each signal, a total of approximately 16 stars, and a comparison was made with the pendulum at the mean epoch. In this manner local sidereal time of these three signals was determined very accurately, without a precision timepiece, as an ordinary chronometer would suffice. In this manner the observer was assured that proper results were being obtained should the pendulum have been disturbed during the day from outside influences.

The pendulum was therefore used principally to carry time from the radio signals received during the day to the mean epoch of the star-set. It was found to be an excellent timepiece over an interval of 12 hours.

The time-observations were made with a Bamberg broken-telescope transit equipped with a hand-driven transiting micrometer.

Various types of signals were received. Arlington and Annapolis used the American system, foreign stations used the vernier-system, that is, 306 beats per five minutes. Some of the vernier-signals had the 60th, 120th, 180th, etc., omitted while others elongated the 1st, 62d, 123d, 184th, etc., for identification. It is hoped that a uniform system will be adopted in the future. Another matter which confronted the various observers was whether to use long-wave or short-wave signals.

Some countries were sending short-wave signals during the longitude campaign and it was felt necessary to record the short-wave signals although no specific mention of them was made in the instructions. In the next campaign the committee should inform each observatory as to which signals, long or short, or both, are desired and as to which are the best radio stations.

The computations of the observations are being reduced by the staff of Mr. Swick of the Coast and Geodetic Survey. The results of 1926 show that the longitude of NIU is 5 hours 22 minutes 39.531 seconds west of the Naval Observatory at Washington, D. C. The preliminary result of 1933 based on 20 Arlington time-signals was found to be 5 hours 22 minutes 39.538 seconds. This value is subject to a slight change when adjusted to the network of the world. The difference between the observations of 1926 and 1933 is 0.007 second. The probable error of the observations as based on these 20 preliminary determinations is 0.006 second. Therefore, the difference between the determinations is about the same magnitude as the probable error. Forty determinations have been made and the preliminary result will be slightly changed when the computations are completed.

It therefore appears that there is no drift of the island of Oahu. If the preliminary results are changed, the change will be so slight that the magnitude of drift will be negligible in relation to the amount desired by the advocates of the displacement-theory. Other observatories may show a slight drift. Although the Observatory at Honolulu does not show any movement, it is desirable that the station be repeated when the third World-Longitude Program is undertaken.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE COAST-LINE AND ISLANDS OF HUDSON BAY--AN IDEAL FIELD FOR GEODETIC ASTRONOMICAL WORK

Noel J. Ogilvie

Almost three centuries and a quarter have passed since the first ship entered Hudson Bay on its voyage of discovery. Sailing southward from the Straits, its intrepid master, Henry Hudson, commenced the exploration of Canada's great inland sea. In the succeeding months he searched both James and Hudson bays for a navigation-route leading to the "Western Sea," compiling as he went a rough sketch-map showing the general form of the Bay, together with the location of one or two of the principal island-groups.

Near the end of October of the same year (1610), encountering frost and snow in the northern central areas, he sailed the vessel south once more to find a more equable climate in which to winter. From the diary of Abacuk Prickett, a member of his crew, there is evidence to support the belief that the vessel was finally wintered near the present site of Rupert House at the southeast extremity of James Bay.

Throughout the long winter months, hardship, monotony, and lack of food bred discontent and antagonism among the sailors. The lengthening days of spring brought a further reduction in the food-ration. Sickness broke out aboard the Discovery and a nervous tension pervaded the atmosphere of the forecastle.

In June, the ship cleared her winter's berth and stood out once more into the Bay only to run foul of floating ice after a few days' cruise. Dissatisfaction became general among the sailors. The majority of the men demanded that further exploration should be discontinued--that they should commence the return journey to England at once. Hudson resolutely refused to compromise and insisted on further investigation.

On June 21, 1611, mutiny flared up among the crew. Henry Hudson and eight of his loyal companions were seized, bound with ropes, cast adrift in a small open boat, and left to the mercy of the ice and waves. The remaining members of the crew manned the Discovery and sailed her back to England.

For over 300 years, the dauntless spirit of Henry Hudson has survived the icy gales of the northern sea. A long line of successors--ship captains, fur-traders, and adventurers imbued with the same determination and the same zeal for discovery, have added little by little to the geographical knowledge and general information pertaining to the Hudson Bay area.

In recent years, the Geodetic Survey of Canada, Department of the Interior, has carried on considerable precise astronomical work, on the western coast, in connection with the establishment of Interprovincial boundary-terminals and the charting of the coastal waters adjacent to the new port at Churchill.

In 1929-1931, a section of coast-line of about 130 miles in extent, constituting the approach to Port Churchill, was mapped and the adjacent waters charted. The control-survey consisted of fourth-order triangulation joining four precise astronomical stations established at intervals along the coast by the Geodetic Survey of Canada. As the nearest net of primary triangulation was at least 600 miles from Churchill, it was impossible to base the local coast-survey on the North American datum.

The boundary-terminal work was interesting and unusual. Special mention may be made of the establishment, in 1930, of the 89th meridian of longitude at the point where it intersects the western coast about 160 miles southeast of Port Nelson. The northerly boundary-terminal, between the Provinces of Ontario and Manitoba, was defined by Act of Parliament in 1912 as the intersection of the 89th meridian of longitude with the western coast of Hudson Bay. Up to 1930, its position had not been determined with relation to adjacent topographical features; nor had any preliminary survey or temporary demarcation been previously undertaken.

The Geodetic Survey party, entrusted with carrying out this undertaking, was obliged to travel from the railway by canoe, a distance of 300 miles, down the Nelson River and along the Hudson Bay coast. The coastal district, for a considerable distance on either side of the boundary-terminal, is undeveloped territory and, as yet, it is only occasionally frequented except by hunters and Indian trappers. For transportation to this place, extra large freight-canoes were used. Adequate capacity was required for the transportation of the heavy instrumental equipment, cement for piers, camp-equipment, and food-supplies, as well as for the personnel of the party.

As the canoes, in the course of the voyage, neared their objective, the geographical longitude became a matter of deep concern to the navigators. Due to the existence of shallow coastal water in that neighborhood, the shore-line could only be approached at high-tide. The arrival of the party at the geographical position, estimated by dead-reckoning to be correct, happened to coincide with the time of low tide. Accordingly, the canoes were beached on the mud-flats, three miles from shore, and several hours spent in waiting for the return of the water.

As the chief of the party stood gazing intently ashore, one of the Indian canoemen, who prided himself on the keenness of his vision, desired to know the object of his search. On being told that the probable position of the 89th meridian of longitude was under consideration, the Indian replied that he would go and look for it, if its appearance was described to him.

The following day, in a shore camp, a preliminary observation for position with a small four-inch transit showed that the camp-site was within a mile of the 89th meridian. This fortunate occurrence saved an additional move along the coast before commencing the precise astronomical observations.

A suitable site for an observation-station was selected on a gravel ridge near the high-water mark. A solid pier of concrete 12 inches by 24 inches by 60 inches, projecting 30 inches above the ground, was built to act as a base for the astronomical transit and also to effectively perpetuate the position of the point. Over the pier an observing-tent was erected and all the instrumental equipment set up.

A broken-axis type astronomical transit, equipped with a travelling transit-micrometer, was used for observing the stars. The master sidereal-chronometer was kept in a well-padded and heat-insulated box resting on the ground. The radio time-signals were received by the aural vernier-method, using an auxiliary chronometer rated to gain one second in fifty on mean time. Short-wave radio was used exclusively, and both the Dominion Observatory and the Washington time-signals were regularly observed. The chronograph was of the portable weight-driven type, which has proved very satisfactory in the field.

Four independent determinations of longitude were made on each of four different nights. About 24 stars were observed in each case, including five or six polars. For latitude, about 35 pairs of stars were observed by Talcott's method.

The observations were, of course, reduced in the field and the position of the pier carefully determined from the mean of all the observations. The small corrections to the observed longitude, due to the errors in the transmission of time-signals, were not known and could not be applied. A simple computation permitted the establishment of the exact position of the 89th meridian with relation to the observation-pier. The meridian was then run a few hundred feet northward to intersect the shore-line.

At the point of intersection, a concrete monument was built. This marker, at the boundary-terminal, was about 12 inches by 12 inches by 48 inches and was sunk in the ground almost flush with the surface. Above it a large wooden beacon was built. A bronze tablet, bearing the name of the Geodetic Survey of Canada, was imbedded in the upper surface of both the observation-pier and the boundary-terminal monument.

By these methods, the position of this important survey-mark will be perpetuated on the ground indefinitely. In addition to the work of demarcation, a survey of the local topographical features was carried out in order to make possible the easy identification of the boundary-terminal either from the ground or from aircraft in flight along the coast.

Adjacent to the coast in this neighborhood an undulating prairie extends inland, broken at intervals by small ravines. At about three miles from the shore, small, scattered spruce are encountered. On further penetration inland, the trees are found to become larger in size and more extensive in numbers. At the five-mile mark, the forest growth is quite dense. Close offshore are situated a few small, low islands, which are known as the East Pens Group.

Both James and Hudson bays contain a large number of scattered islands, ranging in size from small reefs to islands of 50 miles in length. The majority of these islands are of so low an elevation that it makes their location difficult or impossible by triangulation-methods because of a lack of intervisibility. In some cases, groups of several islands may be connected by a small triangulation-scheme based on a local astronomical datum. The Belcher Island Group, in Hudson Bay, has already been surveyed by this method in conjunction with the use of aerial photography. In the majority of cases, however, each isolated island or reef requires the establishment of an astronomical station to determine its position.

Few people, even in Canada, have a correct conception of the general nature of the coast-lines of James and Hudson bays. They may be classified roughly into two principal divisions. The east coast, from Cape Digges on the north to Rupert House at the south, may be characterized in general as an easily approachable rocky shore of considerable elevation, with adjacent waters of sufficient depth for the navigation of medium-sized craft fairly close to shore. Many islands, affording an abundance of shelter, are to be found close inshore. The remaining section, extending along the south and west of James Bay and along the west of Hudson Bay as far as latitude 61°, may be described as involving great stretches of low swampy shores, immense mud-flats and sand-bars, extremely shallow water within two miles of the high-water mark, dangerous shallow-draught entrances to the only available harbors at the mouths of tributary rivers, and a dearth of sheltering islands in the neighborhood of the shore.

One marked exception must be noted--the section of coast in the immediate neighborhood of the new port at Churchill. This section is marked by a rocky escarpment, which rises one or two hundred feet above the sea. The waters adjacent to the coast at this point are of sufficient depth to permit ocean-going vessels to approach the shore. The entrance to Churchill Harbor is deep and free of obstructions, giving ready access to one of the finest harbors in Canada.

On the west side of the 1,500-foot entrance to Churchill Harbor stands the ruins of old Fort Prince of Wales. On the opposite side is the site of Cape Merry Battery. The Fort and Battery are of great historic interest. The construction of this large, stone fortress, built in the form of a square with sides approximately 314 feet long, was commenced in 1733 by the Hudson's Bay Company, and its erection was supervised for a number of years by the celebrated Samuel Hearne. The walls averaged 40 feet in thickness, and on the parapet 40 guns were mounted. This large and expensive fortification was probably not built by the Hudson's Bay Company chiefly for the protection of their own interests, but rather for the purpose of complying with the terms of its Royal Charter which required that it should fortify the country.

With such a fortification, Churchill would naturally be deemed impregnable in those days; yet history informs us that the French, under the gallant La Pérouse, suddenly appeared on August 8, 1782, with three vessels of war manned by scurvy-stricken crews, and demanded an unconditional surrender.

The amazed garrison of 39 men complied with this demand. Without firing a shot, they threw open the gates; whereupon the French took possession, spiked and dismounted the guns, burned the barracks, and sailed away to France with Hearne, his men, and all their valuable furs.

Today, the Fort still remains much as it was left by La Pérouse--its massive walls an imposing landmark on a bleak and treeless promontory, the heavy guns lying among the crumbling masonry and stonework, mere masses of rusting iron.

Travel along the Hudson Bay coast is usually confined either to coastwise ships and power-cruisers that keep 15 or 20 miles offshore in voyaging from point to point, or else to the use of heavy freight-canoes, equipped with outboard engines. These canoes, of a special heavy construction developed by the Hudson's Bay Company, are from 20 to 22 feet in length, with a carrying capacity of from 3/4 to 1 1/2 tons. Being extremely seaworthy and easily handled, they are well adapted for travel in this district.

Travel by canoe along the western coast is seldom monotonous or dull. It is recommended for the brave rather than the fair. In planning a trip the condition of the coast and the stage of the tide must always be kept in mind. The tide, at low-water, leaves bare to seaward, in most sections, from one to three miles of boulder-strewn mud-flats. The immediate shore-line is, in general, no more than five or six feet above the high-water mark. In other places, it is less.

The day's journey is usually commenced by breaking camp at dead of night. The hour of high tide is zero-hour; for only then is there sufficient water to float the canoes near shore. Heading straight out to sea, the heavy canoes are poled or paddled into relatively deep water from two to five miles offshore, where it is safe to start the motors. It is customary then to run on compass-bearings paralleling the coast.

By dawn, the voyagers are often well on their way. Even in daylight, it may be impossible to distinguish the low shore-line with this amount of offing. At best, it appears as a thin flat streak on the horizon. The day's journey, once commenced in this manner, cannot be terminated at will. Until the tide comes in again about 12 hours later, the canoes must be kept at sea. Rain, wind, waves, or tranquil sunny weather must be faced alike in the open.

In extreme cases where dangerous, howling gales, and heavy seas sweep down from the northeast, a landing may sometimes be made, through the surf, on the mud-bars. In such cases, the canoes would usually be wrecked and the cargoes damaged or lost. But the Hudson Bay type of heavy freighter is no eggshell and has been found to weather most surprisingly large seas.

The long day's journey gives ample time for reflection and a study of nature at her best. Schools of white whales, also seals, walrus, and occasionally polar bears are seen in close proximity to the canoes. In the early part of the season, the cool zephyrs off neighboring fields of ice check any undue tendency towards heat-prostration. In fact, the heaviest of winter clothing must be worn.

At intervals of about one decade, the western coast is visited in the fall by devastating storms. Under a combination of northeast gales, low barometric pressure, and high tides, the sea-water rises six or seven feet above its customary level. Smashing seas come pounding in destroying all movable objects in their path. This results in much property damage and loss of life. Indians, in shore-encampments, white trappers, and traders are awakened at night to find their camps or houses in the midst of a swirling, threatening flood. Flight inland, if at all possible, is their only salvation.

On one such occasion, a large sailing-schooner of 30 tons' displacement, belonging to the Hudson's Bay Company, was carried three miles inland and left high and dry among the spruce trees.

But nature is not always wild and turbulent in this district. Sometimes, long periods of warm sunny weather, with blue skies and gentle breezes, make life extremely pleasant along the northern seaboard. In recent years, the new ports at Churchill and Moosonee have sprung into existence to add a new interest to the life of the local residents. But, in general, it is quite certain that relatively small changes have occurred in either the eastern or western coast since the day that Henry Hudson embarked, with his eight companions, on his last long voyage of discovery.

Geodetic Survey of Canada,
Department of the Interior,
Ottawa, Canada

PROGRESS-REPORT ON THE ABSOLUTE DETERMINATION OF GRAVITY AT WASHINGTON

Paul R. Heyl

There has now been completed a set of measurements of g with each of our four silica pendulums, all resting by planes of stellite upon the same agate knife-edge. The results follow:

Pendulum number	Relative flexibility	Mass in kg	g	Average departure from mean
1	1.00	1.1	980.082	0.017
2	0.89	1.9	980.085	0.011
3	0.64	3.6	980.068	0.007
4	0.31	3.6	980.077	0.006

It is of interest to notice the greater precision of the results with the heavier pendulums. This is to be expected, as the more massive pendulums should be less affected by trifling disturbances.

It is also interesting to see that the flexure-correction appears to be comparatively insignificant, apparently cancelling out almost completely in the application of the formula for the reversible pendulum.

The agate knife-edge employed in this series was in almost daily use for nearly two years. Its radius of curvature was measured at the beginning and end of this period with an accuracy of about 15 per cent, and the following results obtained:

	Radius in microns	
Year	Left side	Right side
1932	38	32
1934	165	70

A new series of measurements has been started, using a knife-edge of stellite against planes of the same material.

U. S. Bureau of Standards,
Washington, D. C.

EFFECT OF MOON'S POSITION ON OBSERVED CLOCK-CORRECTIONS

H. R. Morgan

Possible detection of the influence of the Moon on observed clock-corrections has been examined by tabulating according to hour-angle and declination of the Moon the differences of two definitive clock-corrections taken on the average of eight hours apart on the same night. These observations were taken on the 9-inch transit circle at the United States Naval Observatory on 1,535 nights in the interval 1903-1921. The corrections were run together with definitive 24-hour rates and the differences formed as given in Table 1. The differences were grouped every three hours for hour-angle of the Moon at midnight, and for declinations of the Moon +28° to +15°, +15° to -15°, and -15° to -28°.

Table 1--Morning minus evening clock-corrections

Hour-angle Moon	Declination of Moon								
	From +28° to +15°			From +15° to -15°			From -15° to -28°		
	Dt	n	v	Dt	n	v	Dt	n	v
h h	s		s	s		s	s		s
0- 3	-.0050	45	-.0024	-.0009	90	-.0001	-.0023	40	-.0038
3- 6	-.0072	51	+.0015	-.0041	103	+.0003	+.0013	61	+.0015
6- 9	-.0064	45	+.0001	-.0052	87	+.0004	+.0001	63	+.0005
9-12	+.0007	26	-.0005	-.0036	93	-.0004	-.0003	76	-.0012
12-15	+.0049	30	-.0001	+.0016	89	+.0004	.0000	64	-.0003
15-18	+.0054	48	+.0011	+.0043	100	-.0005	+.0009	64	+.0025
18-21	+.0015	73	-.0026	+.0052	76	.0000	-.0057	41	-.0043
21-24	+.0061	60	+.0029	+.0029	72	+.0001	+.0057	38	+.0048

The tabular quantities of Table 1 give the following expressions for Dt for various declinations:

Declination +23°

$$Dt = -\overset{s}{.}0009 \sin h + \overset{s}{.}0037 \cos h + \overset{s}{.}0014 \sin 2h + \overset{s}{.}0004 \cos 2h$$

Declination 00°

$$Dt = +.0006 \sin h + .0031 \cos h + .0000 \sin 2h - .0002 \cos 2h$$

Declination -23°

$$Dt = +.0002 \sin h - .0004 \cos h + .0007 \sin 2h + .0000 \cos 2h$$

These apply in the sense $Dt = a(\sin h \text{ morning} - \sin h \text{ evening})$, etc., h being the hour-angle of the Moon at the time of observation. The probable errors of the tabular quantities and of the coefficients may be taken as of the same order as the quantities themselves.

The time-effect of the Moon on a pendulum is given by Gaillot (Bull. Astronomique, v. 1), as

$$Dt = -\overset{s}{.}0006 \sin 2b \sin 2d \sin h - \overset{s}{.}0003 \cos^2 b \cos^2 d \sin 2h$$

taken between limits of hour-angle h. This effect on clock-corrections for different declinations becomes for

Declination +23°

$$Dt = +\overset{s}{.}0005 \sin h + \overset{s}{.}0002 \sin 2h$$

Declination 00°

$$Dt = .0000 \sin h + .0002 \sin 2h$$

Declination -23°

$$Dt = -.0005 \sin h + .0002 \sin 2h$$

Thompson and Tait (Natural Philosophy, v. 1), give the deflection of the vertical as

$$Dt = -\overset{s}{.}00116(\sin b \sin 2d \sin h + \cos b \cos^2 d \sin 2h)$$

This effect on clock-corrections from equatorial stars at Washington becomes

Declination +23°

$$Dt = +\overset{s}{.}0006 \sin h + \overset{s}{.}0010 \sin 2h$$

Declination 00°

$$Dt = .0000 \sin h + .0009 \sin 2h$$

Declination -23°

$$Dt = -.0006 \sin h + .0010 \sin 2h$$

The expansions include factors for a yielding Earth 1.18 and 1.14.

Taking the pendulum-effect away from the observed values leaves

Declination +23°

$$Dt = +\overset{s}{.}0040 \sin (h + 7\overset{h}{.}4) + \overset{s}{.}0013 \sin (2h + 1\overset{h}{.}2)$$

Declination 00°

$$Dt = +.0032 \sin (h + 5.3) - .0003 \sin (2h + 3.0)$$

Declination -23°

$$Dt = -.0008 \sin (h + 10.0) + .0005 \sin (2h + 0.0)$$

The terms in 2h have fair agreement between observation and deflection-theory, but those in h are considerably larger for the observations. High tide at Washington follows the Moon by from seven to eight hours. Apparently the observations are not as yet accurate enough to give the real coefficients, but they approximate them in order of magnitude.

Helmert (Geodasie, v. 2), gives the terms in the variation of longitude due to motion of the pole approximating a day as

$$Dl = -\overset{s}{.}0006 \cos H + \overset{s}{.}0005 \cos (H - 2M) + \overset{s}{.}0002 \cos (H - 2S)$$

where H is the sidereal time, and M and S are longitudes of the Moon and Sun. These would affect the differences in clock-corrections taken a few hours apart, but on account of the changing phase on mean time their effect would be eliminated for means taken over a year or more.

In Monthly Notices of March 1931, Brown and Brouwer call attention to the fact that there may be other tidal effects. They show the comparison of a pendulum with a crystal-oscillator giving the term $^{s}.00015 \sin 2h$ as given by theory. I am indebted to Dr. Brouwer for valuable suggestions in this comparison.

The quantities found by Loomis and Stetson (Monthly Notices, April 1933) from comparison of Washington and Greenwich time-signals are ten times the size of the variations in observed clock-corrections.

U. S. Naval Observatory,
Washington, D. C.

PROGRESS OF THE GEODETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1, 1933 TO MARCH 31, 1934

C. L. Garner

The Coast and Geodetic Survey produces the bulk of the geodetic work in this country. This work consists of triangulation and leveling for furnishing the horizontal and vertical control-nets, astronomical observations, base-measurements, gravity-determinations, and the operation of two international latitude-observatories. All except gravity and the variation-of-latitude work may be classed as a fundamental part of the triangulation and leveling.

The geodetic work accomplished in this country during the past year is the greatest in our history. This has been made possible by the allotments of funds to the Coast and Geodetic Survey, the greater part of which was for the principal purpose of relieving unemployment in our march toward economic recovery. Since July 1, 1933, the total funds allotted to geodetic work, including the regular appropriation, is approximately $2,600,000. Since April 1, 1933, about $1,000,000 has been spent. The work has been extended into those open areas in most of the states which have not benefited by similar surveys, where public-work projects are under way or planned and where early development seems likely.

The Coast and Geodetic Survey has cooperated with many governmental and outside agencies in the extension of control. Work has been extended in Florida and Tennessee in cooperation with the Corps of Engineers of the United States Army in connection with surveys related to navigational projects and extensive work in the Tennessee River Basin is now in progress in cooperation with the Tennessee Valley Authority. The Bureau has also cooperated with the Forest Service, General Land Office, Reclamation Bureau, North Carolina State Highway and Public Works Commission, and Los Angeles County in California. In fact, field-parties are instructed to tie in to all classes of surveying stations, monuments, towers, and marks of state and Federal agencies where such coordination will be of mutual advantage or in any way assist in producing uniformity and greater efficiency in the extension of all classes of surveys.

Work completed since April 1, 1933, is as follows:

First-order triangulation	5,350 miles
Second-order triangulation	1,200 miles
First-order leveling	20,150 miles
Second-order leveling	14,600 miles
Laplace stations (including observations for azimuth, latitude, and longitude)	29
First-order bases, 11; total length of first-order bases	82.6 miles
Gravity-stations	110

This brings the total of triangulation and leveling accomplished to April 15, 1934, as follows:

First-order triangulation	42,700 miles
Second-order triangulation	1,850 miles
First-order leveling	90,150 miles
Second-order leveling	19,600 miles

The present organization of field-parties is completing more than 1,100 miles of triangulation and 7,000 miles of leveling per month.

It is of interest to note that the work accomplished during the past year includes approximately 1,000 miles of second-order triangulation most of which is along various sections of our coast-lines and is principally for the control of hydrographic and topographic surveys and aerial mapping required in the production of charts. This work is of standard accuracy and uniformity and forms an integral part of the control-system.

Realizing the importance of control-surveys to engineering operations of all kinds, every attempt is being made by the Bureau in the extension of surveys to obtain pertinent information, and to furnish it to the public in a form which will be of the maximum benefit. This has resulted in a number of improved practices, of which the most important are:

(1) At every triangulation-station there is established an azimuth-mark at a minimum distance of approximately 1/4 mile, to which the direction is accurately determined, the distance only approximately. With the geographic position and an azimuth at each station, the engineer has data immediately available with which to extend work or to tie in his local project without the necessity of connecting with an adjacent triangulation-station.

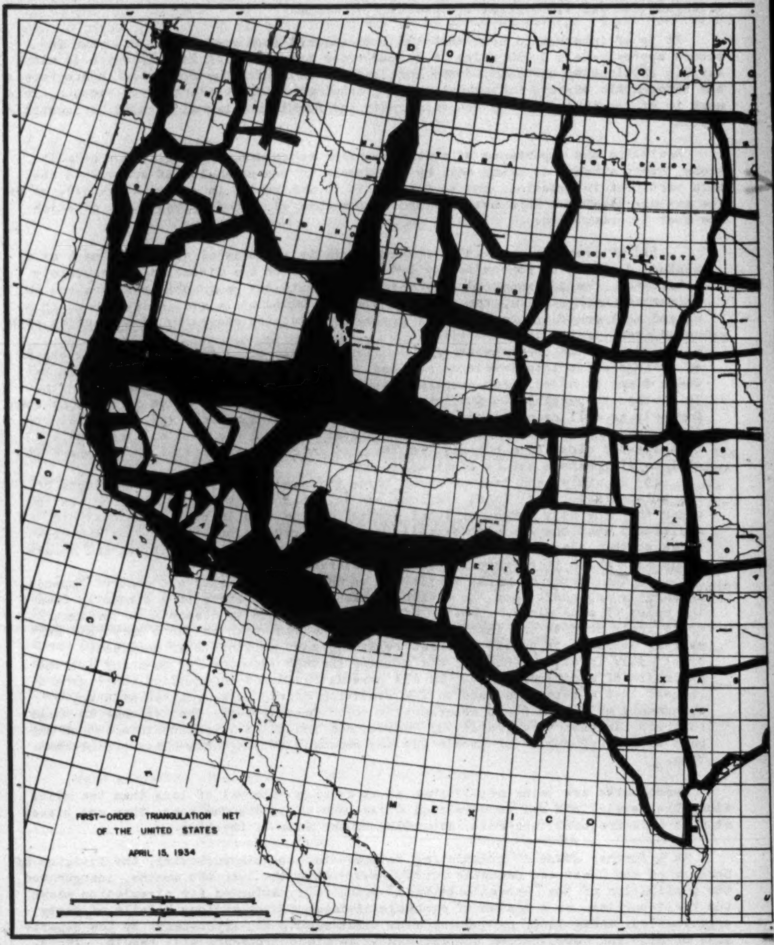
(2) With the development of the Bilby portable steel tower, and the extension of triangulation into developed regions, the most practical length of line is between 8 and 12 miles, with comparatively few lines exceeding 15 miles in length. This makes it possible to furnish a much more uniform distribution of stations than formerly as well as enabling the location of prominent natural and artificial objects near the scheme. In each quadrilateral there is required at least one station located close to a highway, in the most important commercial areas, where it will be of greatest use to local engineers.

(3) In cities and towns of over three thousand population near the route of the triangulation additional stations are established within the city borders in order that any city survey or local control may be tied in to the national net. Additional stations are also established on the grounds of universities and colleges so that classes in field-engineering can have definite positions and directions with which to reference their own observations.

(4) The number of marks available, on which the value of all control depends, is largely dependent upon the attitude taken by the citizens of a community toward the value of such marks. Greater effort is being made to disseminate information as to their purpose and importance. During the last year or two a very real and evident increase in public interest regarding such work has been manifested practically in all sections of the country through requests for data and for the extension of additional work. To all persons furnished information there goes a request that a report be made on the condition of all marks visited with any amendments which are found necessary in their description. The response to these requests has been very gratifying indeed, and indicates a genuine interest on the part of a large number of people who are constantly using this class of information.

Bench-marks are being established at an average interval of less than two miles along the level-lines and in developed areas such as cities and towns they are placed at much more frequent intervals, depending on the size of the city.

As a further means of stimulating interest in geodetic surveying, the Division of Geodesy of the Coast and Geodetic Survey has, within the last two months, inaugurated the publication of the "Geodetic Letter," principally intended for circulation among the field-parties, as a medium of exchange of ideas of the various details of party organization, management, procedure, etc. Thus each party may benefit by the experience of all, and coordination and uniformity in field-procedure will result. It is, of course, true that general instructions cover all phases of the work but these are limited to the more important points and do not go into lengthy details. The "Geodetic Letter" is intended to cover that field which is not touched by other publications or instructions and to act as a means of encouraging whole-hearted interest in the work and organization.

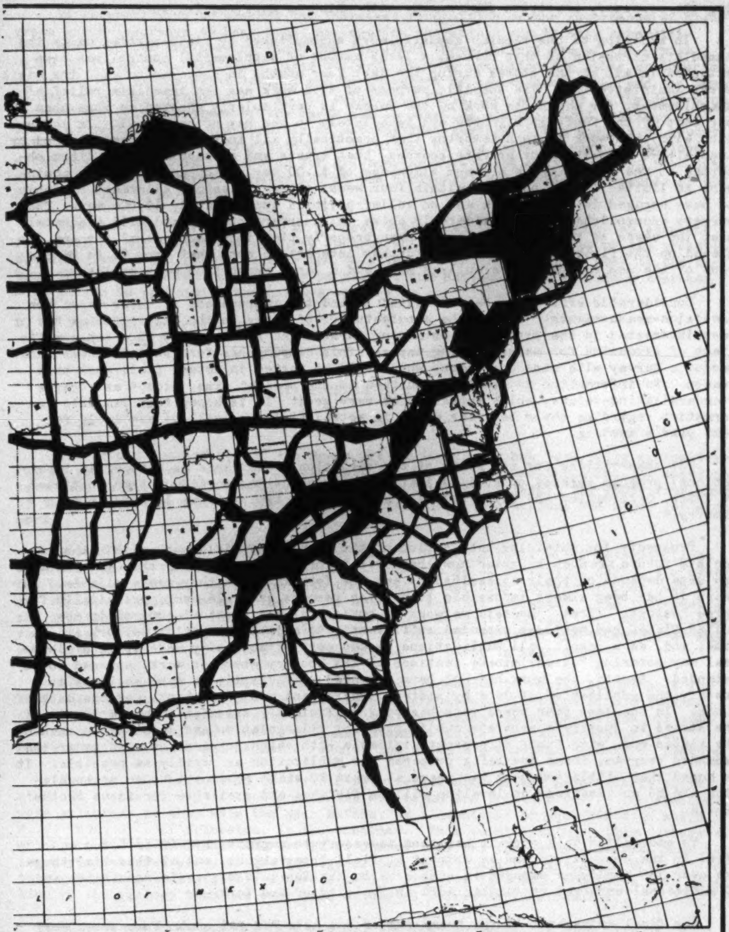


FIRST-ORDER TRIANGULATION NET OF THE UNITED STATES

APRIL 15, 1934

D O M I N I O N
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
IDAHO
WYOMING
KANSAS
NEW MEXICO
TEXAS
M E X I C O

At the beginning of the expanded program considerable difficulty was experienced in obtaining the necessary instruments, particularly theodolites and levels, with which to carry on the work. We were fortunate in obtaining a number of both types of instruments from the Geodetic Survey of Canada and from colleges and universities throughout the country. This made it possible to accelerate the field-work during the interval that instruments were being manufactured.



The demand for precision surveying-instruments in this country is not sufficient to interest the manufacturers in producing them. As a result the users of high-grade instruments have in the past been forced to purchase them abroad or obtain them by contract and specifications from manufacturers in this country. The last method is not productive of the best instruments in spite of any restrictions which may be placed in the specifications. During the last three years, due to the law prohibiting the purchase of foreign instruments, the Bureau has experienced difficulty in obtaining the necessary precision-instruments with which to carry on its work.

In addition to the regular geodetic work accomplished by field-parties under the immediate direction of this Bureau, a large amount of supplemental control has been extended in all of the states during the last four months in cooperation with the Civil Works Administration. The specific purpose of this work was the immediate relief of unemployment, for which the work of the Bureau is particularly adapted as more than 85 per cent of the funds go directly and immediately to the pay of personnel. In connection with this work it is noteworthy that practically all instruments were obtained by loan either from state or private sources, that trucks and automobiles were often obtained at the Government's minimum allowance of $1.00 per month, and that with equipment so limited it was possible within four weeks after the actual allotment of funds to have engaged in useful work and on relief payrolls approximately 10,000 men. The surveys accomplished were considerably above third-order accuracy and will adequately meet the needs of the local engineers when properly tied into the federal net and placed on the fixed datum. It is of further interest to note that from 72 to 85 per cent of the men employed were college men, and a large proportion were engineers.

Considerable effort has been directed toward the improvement of invar-tapes for precision-measurements. One of the manufacturers of invar in the United States has been interested in the problem of obtaining durable and stable alloy of a low coefficient of expansion for manufacturing tapes. This company has furnished the Coast and Geodetic Survey with nine such tapes which will be tested in actual field-work this season. No information is available on them at the present time, except as regards standardization-values, which appear to be very good. It is hoped that reliable information regarding their behavior while in actual field-use will be available for next year's meeting.

The observations for the study of the variation of latitude as part of an international program carried on at five stations throughout the world have been continued at Ukiah, California, and Gaithersburg, Maryland, the two stations located in this country.

Prospects for obtaining publication of the results of field-work within the immediate future are much brighter now than ever before. It is obvious that the value of any data depends on their accessibility and the form in which they are available. For years it has been almost impossible to publish results of field-work, principally for three reasons. First, the main network of horizontal and vertical control in the United States had not been extended sufficiently to adjust the entire network at one time, and, as a result, all publications issued were of necessity made up in a piecemeal way covering indiscriminate sections of the country wherever work happened to be extended. Second, the work had not been extended sufficiently in many sections to justify the publication of data by states. Third, and most important, was the lack of funds. In the last four years work has been sufficiently extended into nearly all of the states to justify a separate publication for triangulation and leveling in each of the states and, with funds at present available with which to carry on work under the expanded program, these are being prepared for publication as rapidly as possible. It is hoped that within the next two years at least 20 state publications on triangulation and 25 publications on leveling will be finished and available for issue to the public.

To accomplish this work it has been necessary to augment the office force engaged in the computation and adjustment of field-observations, and at this time there are over 130 employees engaged in such work in the Bureau's office in Washington and 50 additional employed on similar work in the city of New York.

The final adjustment of the framework of the main Federal control was completed in August 1932. Since that time the work of adjusting the sections of triangulation into the junction-points, together with the adjustment of all subsequent triangulation as quickly as practicable after the records reach this Office, has gone steadily forward. The same applies to the reduction of level-records and the adjustment of various loops into the 1929 General Adjustment for the whole country. With fixed positions and elevations on which to hinge future work, the problems of computing and adjusting new triangulation and leveling will be greatly simplified, and it will thus be possible to furnish final data to the public with greater facility.

It is gratifying to observe the increased recognition of the importance of high-grade control-surveys to nearly all engineering operations and to many scientific problems. In the engineering field the results of these surveys are of the utmost value in irrigation, drainage, river-control, highway-extension and other engineering projects, and in the establishment and perpetuation of county-boundaries and the boundaries of private properties. In the scientific field they are used in the determination of the size and shape of the Earth and in learning how the geoid, or sea-level surface, deviates from the spheroid or mathematical surface. From a study of geodetic data a knowledge of the distribution of densities in the Earth's crust is obtained which may be useful in the search for oil-bearing strata and bodies of ore. The data are also used to determine the extent of the horizontal and vertical movements of the Earth's crust in earthquake-regions.

The most important function of geodesy would seem to be to produce an adequate framework of horizontal and vertical control which eventually will be of the greatest possible use in all public surveys and to stimulate interest in such work to the extent that public-works projects may be planned and executed with a minimum cost and with a view to performing the maximum service to our citizens.

U. S. Coast and Geodetic Survey,
    Washington, D. C.

RECENT PROGRESS IN GRAVITY-WORK

C. H. Swick

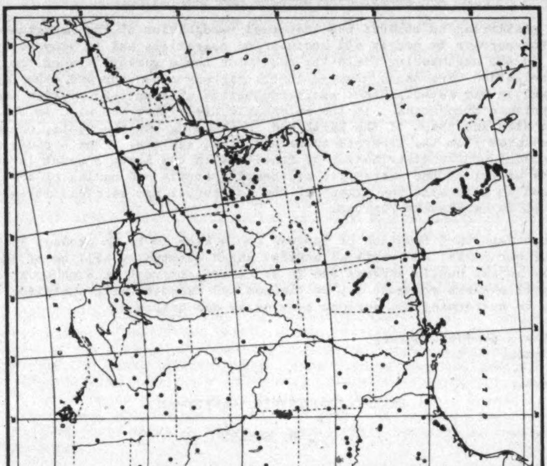
The second year of use of the Brown gravity-apparatus has been fully as successful as the first year. Since the previous meeting of this Section about 110 stations have been determined, in a working time of eight months or less. The other four months of the year were devoted by the party to astronomical observations and other geodetic work.

A year ago gravity-work was in progress in Cuba. A total of 79 determinations were made on the Island by the observer, Lieutenant A. J. Hoskinson, during the season. The work was done in cooperation with the Atlantic Refining Company of Cuba, who paid all expenses except the salaries of the observer and his assistant. The instruments and gravity-truck were furnished by the Coast and Geodetic Survey. Dr. Roy E. Dickerson, Chief Geologist of the Atlantic Refining Company, selected the locations of the stations, and gave very valuable assistance to the party in many ways.

After returning to this country, the party proceeded to Texas, occupying a few stations en route. In Texas they made several check-determinations of old stations near Damon Mound, connected with several local base-stations of one of the oil companies near Houston, and finally made an intensive survey of the Crosbyton Area, where torsion-balance and magnetic results indicated a pronounced structural feature.

In July, the party took up work in Wyoming and Montana and added nearly thirty stations to the survey of that area which was begun the previous year. The stations were selected, as they were the year before, by a committee of geologists of which Dr. W. T. Thom, Jr., of Princeton, is the chairman. This committee, the other members of which are Dr. W. H. Bucher and Dr. R. T. Chamberlin, has for several seasons been making a very careful study of the geology of the region, and the knowledge of this area thus gained has made possible a more detailed study of isostatic anomalies with relation to the geology than has ever been attempted before in this country.

For the past two and one-half months, the gravity-party has been working in southern Florida. A number of determinations have been made on the Florida Keys and across the Everglades and to the northward. Only the preliminary results are available at present, but they show variations in the isostatic anomalies that are quite striking for an area with so little topographic relief. These variations must be caused by peculiarities in the geological structure of the area, and the anomalies show that the abnormal masses must be fairly close to the surface of the ground.



In addition to the work with the Brown apparatus just described, four stations were determined in December 1933 with the old type of apparatus. These stations are on the Island of Oahu, Territory of Hawaii, and were determined by Lieutenant J. P. Lushene immediately after he had completed the World-longitude observations.

Nearly all of the gravity-work of the Coast and Geodetic Survey during the past two years has been done for the purpose of studying rather restricted areas. It has been found that the isostatic anomalies are fairly sensitive to changes in underground structure, and that in most areas they vary more rapidly than was supposed a few years ago. The anomaly-maps, published when gravity-data were meager, show anomaly-lines that, we know now, are entirely too generalized. As soon as additional data are obtained in an area, the anomaly-picture is usually entirely changed. Except for the fact that a number of scattered stations are needed in the Rocky Mountain area to fill in wide gaps in our gravity-survey there, it would seem that the best method for planning future gravity-surveys is to continue to concentrate our efforts in small areas.

At our last meeting Lieutenant Brown told about the new connection between the Washington base-station and Potsdam. The final computations had not been made at that time. A provisional value for Washington (Commerce Building base) of 980.118 gals was finally adopted in June 1933. This value was derived by using both the connection made by Brown and that made by A. H. Miller of Canada in 1928 and 1929 (A determination of the relative values of gravity at Potsdam, Greenwich, Ottawa, and Washington, by A. H. Miller; Pub. Dominion Observatory, vol. 11, No. 2, 1931). Since Brown used at least twice as many pendulums as Miller, his results were given a weight of two and Miller's a weight of one in deriving the mean.

All determinations of gravity made during the past year have been based on the new Washington base-value. A table of all gravity-data in the United States reduced to this new base, and with the isostatic anomalies computed on the International gravity-formula for a depth of compensation of 96 kilometers has been prepared, and will be ready for distribution to interested persons within a short time. There is also available at the Coast and Geodetic Survey a base-map of the United States on which the gravity-stations up to the end of 1933 are shown, and which may be obtained on application to the Director.

The new connection with Potsdam noted above was made for two purposes, (1) to check the United States base-station at the Commerce Building as already explained, and (2) to provide the best possible connection between Potsdam and the Bureau of Standards in order that the absolute determinations made by Dr. Heyl might be compared with the old absolute determinations at Potsdam made by Kühnen and Furtwängler (Bestimmung der absoluten Grösse der Schwerkraft zu Potsdam mit Reversionpendeln by F. Kühnen and P. Furtwängler, Berlin, 1906) thirty or more years ago. The value of gravity at the Bureau of Standards derived by this connection is 980.100 gals. Nine pendulums were used for making the connection and each pendulum was swung twice at the Bureau and once at Potsdam on each of two knife-edges.

In several different countries a great deal of attention has been given lately to the question of developing gravity-apparatus that will give the required accuracy with much less effort and time than that required with the older types. For land-determinations, the three most successful types at the present time seem to be the Holweck-Lejay inverted-pendulum apparatus, the Conyngham two-pendulum apparatus, and the Brown apparatus.

In spite of the fact that the Holweck-Lejay pendulum depends upon the constancy of the elastic properties of a spring, the results obtained with it seem to be uniformly good, judging from published accounts of work done with it. It is perhaps slightly more rapid than the Brown apparatus.

The English apparatus is patterned somewhat after the Meinesz sea-apparatus and has the advantage of eliminating the flexure difficulty which is always a troublesome correction when one pendulum is swung alone. The English method of observing, which Dr. Jolly explained on his recent visit at our office, is unique and very interesting. Many of you have seen published accounts of it.

Two sets of apparatus are used, one at the base-station and one at the field-station. By previous agreement the two observers record at the same time on their chronographs ordinary code-signals over a period of about five minutes, as sent out by one of the radio stations.

At the end of an hour another record is made by both observers. When the field- and base-records are compared the gain or loss of the field-pendulum as compared with the base-pendulum becomes very accurately known. The method is now being tried in East Africa with the base-station still retained in England. The fact that the determinations do not depend upon special time-signals adds special interest to the method.

As far as rapidity of work is concerned, none of the three types of apparatus mentioned above has any great advantage over another. The Holweck-Lejay apparatus is small and easily transported. It is very sensitive to certain types of disturbance, particularly variation of level-position. The English method has the disadvantage that the computations cannot be made in the field as the field chronograph-sheet must be compared directly with the base-sheet. This is only a minor point, however, and is not a criticism of the apparatus itself. All three types are apparently superior to older types formerly in use. It is hoped that the present wide-spread interest in gravity-apparatus will result soon in a still better type than any so far developed.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF SEISMOLOGY

Washington, D. C.
April 26, 1934

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SEISMOLOGICAL PROGRESS-REPORT

N. H. Heck

An annual taking of stock of seismological progress is a useful procedure since it is both instructive and stimulating. In a subject with so many subdivisions covering a wide range of activity it is by no means easy for any one person to cover the field. The writer has volunteered to do this because his official duty requires him to keep in touch with all branches of seismological effort in order that the work of the Coast and Geodetic Survey in this field may be coordinated with other activities. In previous reports it has been customary to list each organization with a statement of accomplishment of each. In the present report the alternate plan is followed of listing the activities and referring under each to the appropriate organizations. The following review of activity must not be considered exhaustive. There are probably omissions of activities that are as important as those included. If such omissions are noted, information regarding them will be welcomed.

Teleseismic stations and instruments

Oak Ridge Observatory, Massachusetts--There have been no changes in the list of stations reported last year and no important changes in installations except those listed below. The new seismological station of Harvard University at Oak Ridge Observatory, Harvard, Massachusetts, replaces the former station long maintained in Cambridge. The new station is among the most completely equipped in the country. The equipment includes Milne-Shaw, Wood-Anderson, and Benioff instruments.

The Franklin Institute, Pennsylvania--The instruments for the station of The Franklin Institute are now practically ready for installation. Dr. Howard McClenahan, Secretary of the Institute, has made an important contribution to seismology by permitting his Wenner seismometers to remain in Washington until the completion of shaking-table tests at the Bureau of Standards made jointly by personnel of that Bureau and of the Coast and Geodetic Survey.

Des Moines, Iowa--It is understood that good progress is being made on the construction of a seismograph in Des Moines, Iowa, to be privately operated. The pendulums are of the Bosch-Omori type and registration will be on smoked paper. A station in this region will be very desirable in view of the present and somewhat unsatisfactory instrumental control on strong earthquakes in the western mountain region, such as that which recently occurred in northern Utah.

Ukiah, California--Improvements have been made to seismograph building at the Coast and Geodetic Survey International Latitude Station to reduce wind-effect on records.

Sitka, Alaska--The Wenner instruments installed at the Sitka Observatory of the Coast and Geodetic Survey late in 1932 have given excellent results. Microseisms have ordinarily not proven excessive.

College, Alaska--The long-expected station at the Alaska Agricultural College and School of Mines should soon be in operation with McComb-Romberg instruments.

Honolulu, Hawaii--At the station of the Coast and Geodetic Survey at the University of Hawaii, the speed of registration was doubled without other instrumental change, with greatly improved interpretation of records.

Huancayo, Peru--This station at the Huancayo Magnetic Observatory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington made important contributions during the year with special usefulness in determining epicenters in the Southern Hemisphere.

Montezuma, Chile--The Bosch-Omori instrument transferred from the Panama Canal to the Smithsonian Institution Solar-Radiation Station gave excellent records at a strategically located station. The installation of an astronomic clock in August 1933 greatly enhanced the value of the records.

No other important changes are known, except that some instruments in the next group give excellent teleseismic records.

Nearby earthquake stations

No addition has been made to the six stations of the Seismological Research Laboratory in southern California for earthquakes of light to moderate intensity. A portable station, however, is now available which is carried in an auto-trailer. The seismograph is set up at the best available site and covered with a cylindrical housing but the rest of the apparatus remains on the trailer. With rock-foundation for the seismograph the results are almost as good as at the regular station, but not quite so good with other foundation.

The wave-seismograph of the Seismological Research Laboratory at Pasadena, California, with name changed to linear-strain seismograph, has been improved and in addition to its normal function has proved very successful in recording S- and L-waves of periods of 60 and 90 seconds. There is of course no trouble with tilt which is usually a serious handicap to recording long-period waves.

There have been no additions to the stations in the San Francisco Bay Region.

Strong-motion stations

The Coast and Geodetic Survey has installed twelve accelerographs and eleven strong-motion seismographs during the past year in California in addition to one accelerograph at Balboa Heights, Canal Zone. New accelerographs now under construction for the Coast and Geodetic Survey are equipped with drums for paper 12 inches wide which will greatly reduce liability of loss of record during a severe earthquake. Other improvements include new design for tape-attachment and new electromagnetic timing-device designed for placing simultaneous time-marks on different instruments in the same building.

The short-period accelerometer developed by the Massachusetts Institute of Technology has been completed but it has not yet been possible to put it into active use for recording earthquakes.

Eleven of the strong-motion seismographs developed at the University of Virginia have been installed and are in operation.

The Coast and Geodetic Survey has developed instruments for recording and observing vibrations in buildings and also a device for placing sustained vibrations into buildings. Both of these instruments were developed after consultation with the Bureau of Standards as to certain details.

Instruments for recording building vibrations, especially for simultaneous recording on different floors of the same building have been developed by California Institute of Technology with the cooperation of Seismological Research Laboratory.

An instrument for determining earthquake-stresses in frame structures has been developed at the Massachusetts Institute of Technology.

Analysis of records and travel-time tables

Much attention is being given to these subjects and the principal activities will be listed.

As regards teleseismic work, Macelwane has issued in mimeograph form "A preliminary table of observed travel-times of earthquake-waves for distances from 10° to 180°." Closely associated work is that of Hodgson and Gold in Canada. Gutenberg has studied the travel-times of the Long Beach Earthquake of 1933 and Byerly of the Nevada Earthquake of 1932. Neumann is working on identification of wave-groups between P and S. Dahm is using recent travel-time curves to study discontinuities within the Earth. Brunner is working on deep-focus earthquakes. Leet and Bradford are studying microseisms.

In connection with study of nearby earthquakes, Gutenberg has announced that he finds additional layers to those of Jeffreys and has assigned thicknesses to the layers. He has announced the P'P'P'-phase and has done other important work.

Gutenberg and Richter have shown the advantages of using geocentric latitudes in the calculation of epicentral distance.

Shaking-table tests of instruments have been made by Dyk at the University of California and by Wenner and McComb at the Bureau of Standards. At the latter place instruments of high magnification such as the Wenner are being successfully tested with simultaneous measurement of the motions of the platform.

Determination of epicenter

Thirty-three preliminary determinations of epicenter were made during the year in the cooperative program of Science Service, the Coast and Geodetic Survey, and the Jesuit Seismological Association. A new code facilitated the transmission of more complete messages at less cost.

The above-mentioned improvements to travel-time tables add to the accuracy of epicenters and also to the better understanding of the interior of the Earth and of the depth at which earthquakes occur.

Heck, recognizing that the list of principal epicenters of Turner for the years 1913-21 is no longer adequate on account of much additional information, has prepared from records of the British Association for the Advancement of Science and International Seismological Summary a mimeographed list for the periods 1899-1910 and 1913-29 (except for the last quarter of 1929) inclusive. The gaps are now being filled with the arrival of the International Seismological Summary for the last quarter of 1929 and for 1911-12 Neumann has revised Klotz' epicenters, especially in cases where the latter has expressed doubt as to correctness.

Non-instrumental earthquake-information

The system of collection of non-instrumental reports of earthquakes continued as in previous years and also the correlation of the information with that derived from instrumental studies, especially by the Seismological Research Laboratory, the University of California, the Jesuit Seismological Association and the Coast and Geodetic Survey. In regard to the western third of the country, the collection of reports at San Francisco continued but the compilation was transferred to the Coast and Geodetic Survey at Washington. A preliminary report in considerable detail is issued for local use and then a summary of all activity in the country appears in the annual publication "United States earthquakes" of the Coast and Geodetic Survey. All of these reports are so arranged as not to invade the field of the special investigator.

Geological studies of earthquake-regions

In addition to the investigations in California which are going on continuously, special investigation has been made of the Nevada earthquakes of December 20, 1932, and of 1934 by Gianella of the University of Nevada and Callaghan of the United States Geological Survey. The Utah Earthquake of March 12 has been investigated by Professor Pack of the University of Utah.

Seismic sea-waves or tidal waves

During the year none has been recorded on tide-gauges of the Coast and Geodetic Survey or observed on our shores. There was a small wave reported on the northwest coast of Luzon, Philippine Islands, from the earthquake of February 14, 1934.

Heck has compiled a list of 224 tidal waves from earliest recorded to the present time, and the list will be published by the International Commission on Raz de Marée. Information regarding such waves is now compiled for the United States and the regions under its jurisdiction by a committee of the American Geophysical Union of which Heck is chairman with members from the United States Hydrographic Office, the United States Weather Bureau, Johns Hopkins University, the University of California, as well as the Coast and Geodetic Survey.

Miscellaneous

Though not belonging in the field of seismology, building design is very closely related. The strong-motion records, though they give much valuable seismological information, have been obtained only because of demand for the information for use in engineering. All large structures such as buildings, bridges, dams, and elevated tanks are designed with regard to available information. Shaking-platform tests at Stanford University have related especially to earthquake-effects on large masses of water in connection with design of dams and associated structures.

No attempt at bibliography will be made, as this is well taken care of by the Bibliographical Bulletin issued by the Dominion Observatory, Ottawa, Canada. The volume on seismology which was sponsored by the National Research Council and prepared under the general direction of Macelwane has been issued. Progress has also been made by Macelwane on his book which is part I of "Introduction to theoretical seismology." Part II by Sohon was published in 1932. It suffices to say that such organizations as the American Society of Mechanical Engineers (Applied Mechanics Division) have held meetings relating to earthquake-effects. The American Society of Civil Engineers is much interested. The "Engineering News-Record" has in almost every number an article on some phase of the subject. There is wide range of attention to and publication of subjects in the Seismological Society of America and its Eastern Section.

During the year the only important earthquake-activity in the United States was in the western mountain region, with earthquakes in Nevada on June 25, 1933, and in Utah on March 12, 1934.

Crustal movement either at the time of an earthquake or otherwise has received considerable attention. The Coast and Geodetic Survey has done both triangulation and leveling in California. In addition, special levels were run in the area of the Nevada Earthquake of December 20, 1932, and plans have been made for rerunning of lines in the region of the Utah Earthquake of March 12, 1934.

Tiltmeter-operation by the Coast and Geodetic Survey and the University of California has been carried on at Berkeley with some loss of record because of difficulty of keeping water out of the pits where the instruments are installed. Work started in April 1933. Only earthquake in this region was that of May 16, 1933.

Statistics of station-operation

Table 1 summarizes the statistics of station-operation for the past year.

Table 1--Statistical summary of station-operation, April 1, 1933 to April 30, 1934

Organization	Stations			
	Teleseismic	Near earthquakes	Strong-motion earthquakes	Inactive
Coast and Geodetic Survey and cooperating stations.......	8	..	33[a]	1
Jesuit Seismological Association........................	11	1	..	5
Carnegie Institution of Washington and California Institute of Technology......	2	6	1	..
University of California and cooperating stations.......	1	3	..	..
Other universities...........	10	..	..	7
Other institutions or individuals..................	2	2	..	1

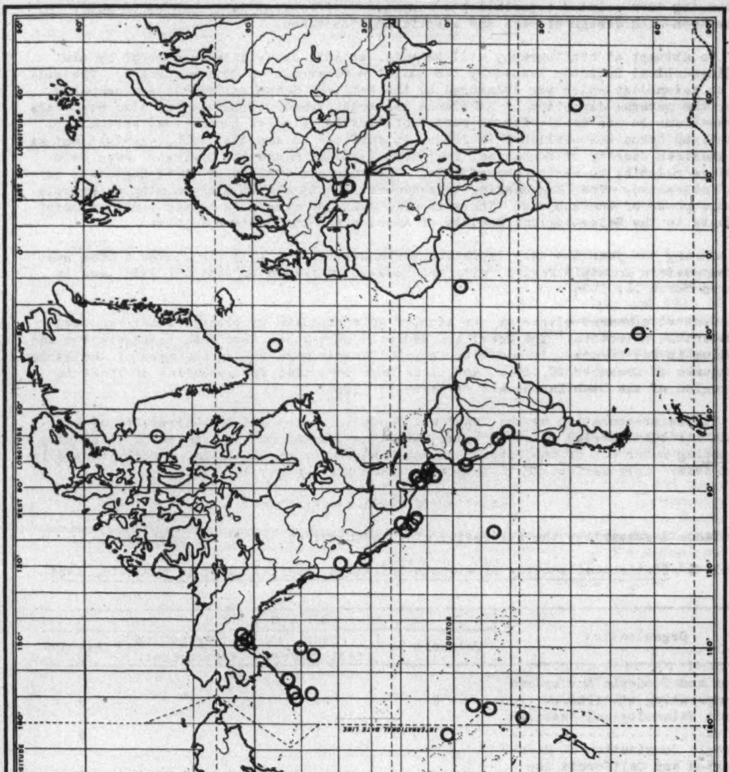
[a] Including one at Balboa; 21 of these since May 1, 1933.

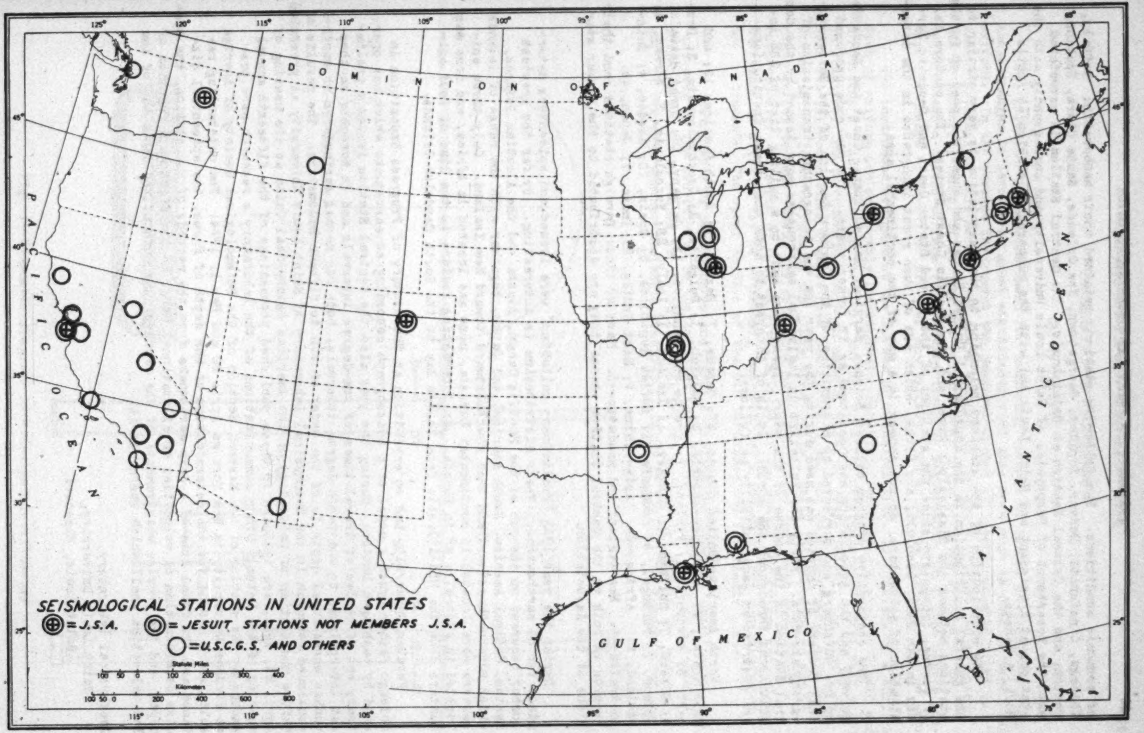
U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION FOR 1933

J. B. Macelwane, S.J.

The work of the Jesuit Seismological Association, which is a voluntary organization of seismological stations which are owned and operated by the Jesuit universities and colleges in the United States, was somewhat curtailed during the year 1933 because


JESUIT SEISMOLOGICAL ASSOCIATION EPICENTERS 1933
EAST 30° LONGITUDE
WEST 90° LONGITUDE
EAST 150° LONGITUDE
EQUATOR
INTERNATIONAL DATE LINE



SEISMOLOGICAL STATIONS IN UNITED STATES

⊕ = J.S.A.
◎ = JESUIT STATIONS NOT MEMBERS J.S.A.
○ = U.S.C.G.S. AND OTHERS
DOMINION OF CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
Statute Miles
100 50 0 100 200 300 400
Kilometers
100 50 0 200 400 600 800
125°
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
45°
40°
35°
30°
25°

of economic conditions. The following stations retained their membership: Buffalo, Chicago, Cincinnati, Denver, Fordham, Georgetown, New Orleans, Santa Clara, Spokane, Weston, and the Central Station at Saint Louis. The Central Station is associated with the Department of Geophysics of Saint Louis University and consequently with the stations at Florissant and Saint Louis and with the cooperative station at Little Rock, Arkansas.

The distribution of the stations belonging to the Association is very similar to the general distribution in the continental United States and shows the need of further stations between the Mississippi River and the Pacific Coast States. The picture is, of course, incomplete since the stations of the United States Coast and Geodetic Survey in San Juan, Honolulu, and Sitka, which are of such great importance in the determination of epicenters, do not appear in a map of the continental area.

The cooperative program between Science Service, United States Coast and Geodetic Survey, and the Association was continued as in former years. The new code proposed by Dr. Gutenberg and perfected by a committee of the Eastern Section of the Seismological Society of America was used during the year for the telegraphic transmission of earthquake-data. Fifty-one bulletins on individual earthquakes were issued by the Central Station in the course of the year. These were sent to a mailing list of 288 institutions throughout the world. It is of interest to note that these institutions are distributed geographically as follows:

North America--United States, 67; Canada, 7; Mexico, 9; South America, 13; and West Indies, 2. Europe--Austria, 3; Belgium, 1; Bulgaria, 1; Czechoslovakia, 3; Denmark, 3; Esthonia, 1; Finland, 1; France and mandates, 13; Germany, 16; Great Britain, 8; Greece, 1; Holland, 2; Hungary, 1; Ireland, 1; Italy, 28; Yugoslavia, 3; Norway, 1; Poland, 1; Portugal, 8; Roumania, 1; Soviet Republics, 3; Spain, 10; Sweden, 4; Switzerland, 3. Africa--8. Asia--China, 7; East Indies, 2; India, 7; Japan, 44. Australia--5. New Zealand and mandates--3. Many of these foreign stations send their reports in bulk to the Central Station whence they are distributed to the member stations of the Association.

During the year 1933 "Preliminary bulletins" were issued and epicenters determined for 55 earthquakes. Their distribution is interesting. By far the greatest number occurred on the rim of the Pacific Ocean, Alaska and the Aleutian Islands, Mexico, Central America, South America, and Japan, together with the range of islands which run southeastward and then southwestward toward New Zealand. Only three epicenters were located in continental Eurasia, none was located in Africa, and none was located in Australia or in Canada. An interesting feature is the line of four epicenters down the Mid-Atlantic from Baffin Bay to the South Sandwich Islands.

Fordham University had on exhibition at The Century of Progress Exposition in Chicago Father Lynch's model of a seismograph recording an earthquake which was operated by pushing a button. During the year also the Central Station issued a preliminary set of tables of travel-times of one-degree intervals and in November another set interpolated to one-tenth-degree intervals, both for normal earthquakes or earthquakes whose focal depth is of the order of ten to fifteen kilometers. The results of continued research in the Geophysical Laboratory of Saint Louis University as presented before the Section of Seismology of the American Geophysical Union at the meeting of April 26, 1934, are included in these published proceedings of the fifteenth annual meeting of the Union. Other communications of the Laboratory's research were presented at the meeting of the Eastern Section of the Seismological Society of America at Fordham University in New York on April 30 and May 1, 1934. The outstanding results are a method for the determination of the depth of focus, the epicentral distance and the focal time of a deep earthquake from the records of one station, the precise determination of velocities of dilatational waves in the Earth as a function of depth, and the precise measurements of the depth of the core of the Earth and of the low-velocities shell which surrounds it.

Geophysical Laboratory,
    Saint Louis University,
        Saint Louis, Missouri

INSTALLATION OF TILTMETERS

G. E. Merritt

The tiltmeter is an instrument for measuring changes of level, particularly such small changes in level that great magnification of some sort must be used to make them evident. In the present instrument the powerful method of interference of light is used. By means of this method very small changes in the angle between two surfaces can be measured; hence, if we have one surface that tilts with the surface to be measured and a second surface that remains level we can measure, in a most direct manner, the change of level, or tilt, of any surface upon which the tiltmeter can be set.

The instrument designed at the Bureau of Standards (Fig. 1) consists of a shallow dish of uniform and preferably low-expansion material, containing a viscous liquid and supporting a plane-plate on the lower surface of which reference-marks have been ruled. In practice, the instruments have been made of glass or fused quartz, the liquid has been oil (although other liquids have been tried), and the reference-marks have been etched in the lower surface of the glass cover-plate. These reference-marks are at right-angles to each other, for obtaining north-south, and east-west components, respectively. A length of 6.06 cm gives a value of one second per fringe and, since one-tenth of a fringe may be estimated, one-tenth of a second is the sensitivity of the instrument. The upper surface of the oil furnishes the invariable plane.

In instruments of precision we must make a distinction between "sensitivity" and "accuracy". The sensitivity is the smallest amount which can be read as a definite difference. It is stated in the units which are to be measured and in the present case is the same whether the angle measured is large or small. The accuracy, on the

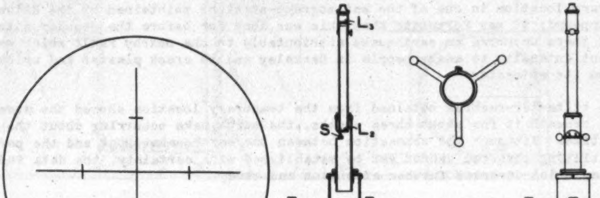


Fig. 1--Schematic diagram, interferometric-tiltmeter other hand, is the degree of faithfulness with which the instrument responds to the appropriate stimulus. It may usually be stated in percentage of total stimulus. In the present case the accuracy was found by exhaustive comparisons and tests to be of the order of 0.02 per cent provided the reference-marks are of the right length. The reference-marks on the instruments installed at Berkeley are of the right size to about one-tenth of one per cent; hence, for movements of the order for which the instrument was designed (40 seconds of arc or less), the accuracy exceeds the sensitivity by a satisfactory amount.

Tilts of the Earth are going on to some extent at all times and places, but the Japanese seismologists have for some time surmised that a particular pattern of tilts might conceivably precede an earthquake and that if this pattern could be determined prognostication of earthquakes might be achieved. It was for this purpose before all others that the interferometric tiltmeter was designed.

The installation of four tiltmeters at Berkeley, California, adjacent to the north end of the Hayward Fault, was a cooperative enterprise of the United States Coast and Geodetic Survey, the University of California, and the Bureau of Standards. I was sent to Berkeley to install and adjust the instruments. Figure 2 is a diagrammatic representation of a complete installation of one unit. Three of these were built, one on each side of the Fault and one about 200 yards further back. Where possible the pits were sunk through the overlying soil and for some distance into the rock so as to get a solid foundation. The pits were all about ten feet deep. The cost of the units were, on the average, $600 each, exclusive of the expense of sending a man to install them. This cost was divided as follows: Tiltmeter, $50; viewing-instrument, $200; house, $200; pit (including corrugated iron culvert-pipe lining), $85; electric wiring and miscellaneous, $65.

While waiting for the preparation of the regular sites I installed a tiltmeter in a temporary location in one of the seismograph-stations maintained by the University. As it happened, it was fortunate that this was done for before the regular sites were prepared there occurred an earthquake attributable to the nearby Fault which was of sufficient intensity to awake people in Berkeley and to crack plaster and brickwork nearer to its epicenter.

The tiltmeter-records obtained from the temporary location showed the movement of the rock beneath it for about three months, the earthquake occurring about the middle of this time. Although the connection between the earthquake-shock and the particular type of tilting observed cannot yet be established with certainty, the data indicate a phenomenon which deserves further attention and study.

For the first five weeks the above-mentioned tiltmeter performed very much as similar installations have done in Washington, most of the movements being readily correlated with temperature. On April 20, 1933, however, it began to show that the rock-strata were no longer responding in a normal manner to the seasonal changes in temperature, but were tilting only through small amplitudes and with many changes of direction so that for 16 days after that date the position indicated was never more than one second of angular tilt from its position of April 20, 1933. Imamura, in a paper entitled "The pre-seismic Earth-tilting and mechanism of occurrence of the Kii Earthquake of July 4, 1929" (Proc. Imperial Academy, v. 5, 1929), mentions the occurrence of a similar motion and calls it a "tilt-storm" although, as he says, it seemed to indicate, in that case, a decreased rather than an increased amount of movement. He noted that after several days of this tilt-storm a rather larger tilt was recorded and that 24 hours later the earthquake occurred.

Consequently when on May 8, 1933, it was found that since May 6 (see Fig. 3) the rock had tilted toward the southeast about six seconds, our interest was greatly increased. From May 9 to 15, 1933, a progression of small tilts occurred, tending in general, however, back toward the tilt-storm position and aggregating about 1.1 seconds. On May 16, at 3:45 a.m., a sharp earthquake was recorded at Berkeley by the seismographs situated in the same room as the tiltmeter.

At the regular time of reading, which was four hours after the earthquake, the rock-strata were found to have returned to an inclination almost identical with the position occupied during the tilt-storm, having moved 3.6 seconds since the last read-

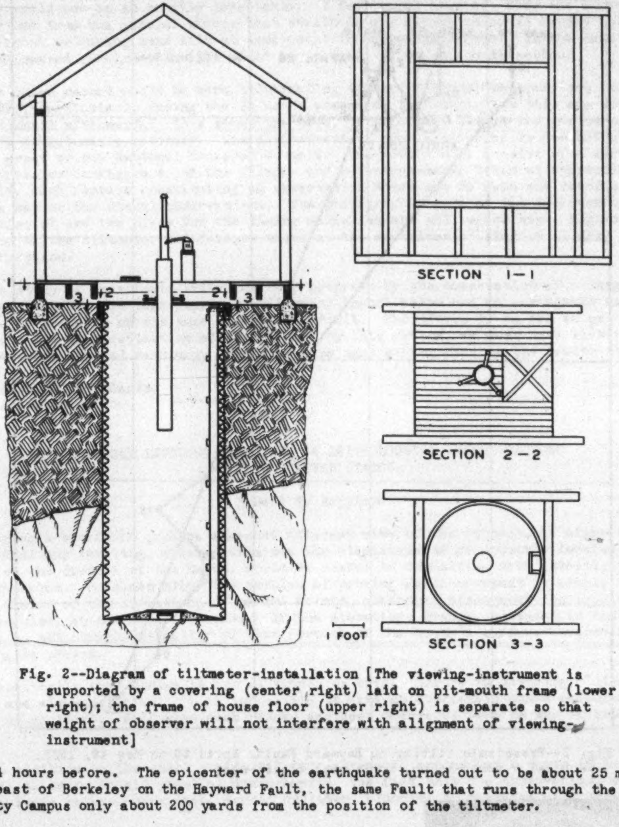


Fig. 2--Diagram of tiltmeter-installation [The viewing-instrument is supported by a covering (center right) laid on pit-mouth frame (lower right); the frame of house floor (upper right) is separate so that weight of observer will not interfere with alignment of viewing-instrument]

ing 24 hours before. The epicenter of the earthquake turned out to be about 25 miles southeast of Berkeley on the Hayward Fault, the same Fault that runs through the University Campus only about 200 yards from the position of the tiltmeter.

The rock then, after an "Imamura tilt-storm," had tilted about 6 seconds down along the direction of the Fault toward the epicenter of the coming earthquake. During the following week it showed a tendency to return toward its former position, and then further tilted 3.6 seconds in one day, which included the time of the earthquake, to a position not far from that which it had occupied previous to the initiation of the unusual movement.

The movement of six seconds observed previous to the quake occurred in two days (no reading was taken on Sunday, May 7). The movement of 3.6 seconds which occurred during the 24 hours including the earthquake was therefore the largest movement recorded for any one day during the three months for which these records are available.

At first glance it might seem that although tiltmeter-records might be of use in

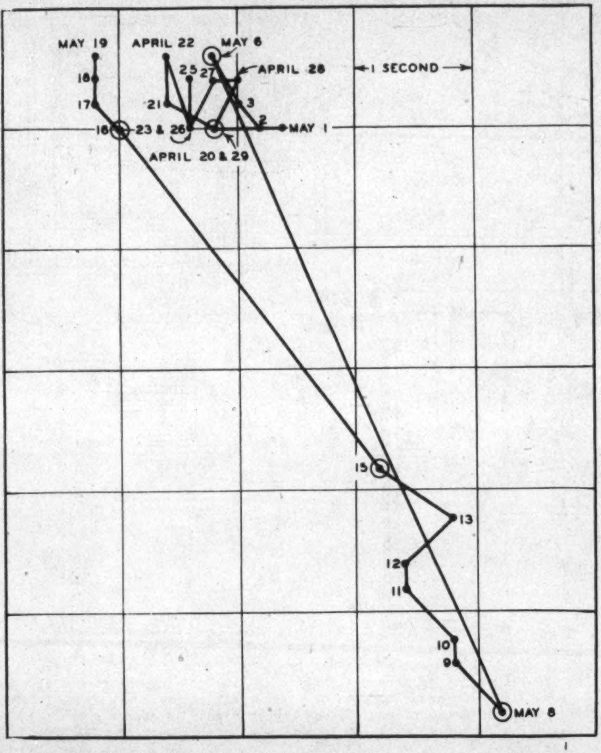


Fig. 3--Preseismic tilting on Hayward Fault, April 20 to May 19, 1933; vertical = north-south, horizontal = east-west

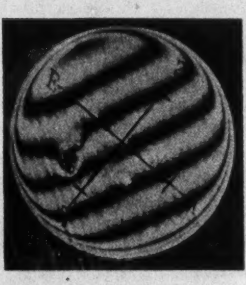


Fig. 4--Fringes as seen in the tiltmeter [To read, the number of fringes between the terminal-lines of the north-south reference-mark, including fractions, are counted and subtracted from the previous reading (or from a "zero") and this distance laid off in a vertical direction on the chart from the plot of the previous reading, or from zero; the same is done for the east-west reference-mark; then the resultant vector will be a representation of the tilt between the two times in direction and amount.]

the case of vertical-movement faulting, the strains set up by horizontal-movement faulting would not be so readily detectable. I feel sure, however, from the above experience and from the general theory that strain in any direction could hardly be possible without producing some tilt at some point in the neighborhood. In the case of very deep-seated strains the tilts might be so small as to escape detection.

The above record would be more illuminating if more frequent observations had been taken, particularly during the 24 hours preceding the shock, but this was not realized until afterwards. This shows the need, particularly during the period of study, of an automatic recorder. The development of such a recorder is now being made under a grant of the National Research Council. The record will consist of a series of pictures, as in Figure 4, of the fringes and reference-marks taken at appropriate intervals, each picture constituting an observation which may be read and recorded in the same way as the visual observations. The photographic part of the instrument has been perfected and the plans for the timing mechanism are well under way. Figure 4 is a picture of the tiltmeter and fringes taken at the experimental station at Cove Point, Maryland.

The study of preseismic tilts can only progress by the observation of a large number of earthquakes and that implies a tiltmeter-installation and an earthquake on the same fault, probably on the same part of the fault. Therefore, if we are to get anywhere with the prognostication of earthquakes by this method, we must have either many tiltmeters distributed over many faults or else many earthquakes on the faults covered.

U. S. Bureau of Standards,
Washington, D. C.

FIRST-ORDER LEVELING AS AN AID IN SEISMOLOGICAL INVESTIGATIONS IN THE UNITED STATES

Howard S. Rappleye

Taking a broad and perhaps somewhat tolerant view of the subject, it might be stated that any leveling, which determines the elevations of permanently located points on the surface of the Earth, would be useful in connection with investigations of earthquakes. Fundamentally, the problem of proving Earth-movement is simply the determination of the elevations of marked points, scattered throughout the area under consideration, at suitable intervals. If the elevations change, movement is indicated. If they do not change, stability of that portion of the Earth's surface covered by the leveling is proven.

Practically the problem is not as simple as this. Errors in leveling, "like the poor," are always with us. It is impossible to make an absolutely exact measurement, except by accident. Even when such a lucky accident occurs we have no way of knowing it.

In addition to the small accidental and systematic errors which occur in leveling and, in fact, in all physical measurements, the fact that the observations are made by human beings means that, sooner or later, blunders or mistakes will occur.

In order that the work may be done in such a way as to minimize the effect of the small accidental and systematic errors and, also, to reduce to a minimum the chances of blunders or mistakes being made, it is necessary to adopt an observing program which is extremely rigid in all respects.

To take what is perhaps a fantastic illustration, let us assume for purpose of argument, that an earthquake could occur and remain confined to an area closely approximating that of one city-block. Also, let us assume in this illustration that movement of several inches occurs during this earthquake. It would be possible then, with comparatively crude leveling methods, to prove this movement and to get at least an approximate idea of its size. All that would be necessary would be to level in from undisturbed bench-marks in the adjoining blocks and determine the new elevations of the marks in the disturbed area. The difference between these new elevations and the old elevations for the same marks plus or minus the unknown errors in leveling would represent the change in elevations due to the earthquake.

In the case cited, the errors in leveling, even with comparatively crude equipment, might be only a small fraction of an inch and, since we have assumed that movement of several inches occurred, we would be in a position to say with certainty that the bench-marks had moved and approximately how much.

Unfortunately earthquakes have a habit of spreading over a much larger territory than a city-block and, also, many of them occur with resulting vertical displacements of only slight amounts. To go back 100 miles or more to undisturbed bench-marks and then extend leveling into the disturbed area with such a degree of refinement that movements of an inch or so can be detected is an entirely different problem and it is for this reason that the qualifying adjective "first-order" appears in the title of this paper.

Naturally, the more accurate the leveling which originally determined the elevations of the marks and which is run after a shock has taken place, the smaller is the movement which can be detected over a given area. Also, the more accurate the leveling, the larger is the area over which movements of a given size can be detected and pointed out with some degree of certainty.

The Federal Board of Surveys and Maps has set up, in connection with its specifications for control-surveys, and with special reference to leveling, four classes of leveling, that is, first-, second-, third-, and fourth-order leveling.

First-order leveling is known as leveling of high precision and is run with special instrumental equipment and with all sorts of precautions in the observing program designed to insure a high degree of precision and to guard against the possibility of blunders remaining undetected. First-order leveling is run twice, in opposite directions, and the lines are broken up, by means of temporary or permanent bench-marks, into sections of from a half-mile to a mile or more in length. The runnings in opposite directions over these sections must check each other within very close limits or rerunning is required until the proper check is obtained.

The second-order leveling may be double-run or not, depending on the instructions issued for the work, but in case it is double-run, the limit of error allowed between the forward and backward runnings over a section is a little more than double that for first-order leveling.

Third-order leveling is approximately equivalent to a good grade of wye-leveling, such as is run by engineers in connection with construction-work.

Fourth-order leveling is really quite crude and the required accuracy can be obtained by vertical-angle measurements with an ordinary engineer's transit or plane-table outfit.

To take a concrete illustration, the Coast and Geodetic Survey a number of years ago extended leveling three ways out of El Centro, California, the line to the west reaching San Diego, California, the line to the northward reaching to Riverside, California, and the line eastward going to Yuma, Arizona, and beyond. A year or so after this leveling had been completed, an earthquake occurred, which, I believe, centered around Brawley, California. It was decided to rerun the lines three ways out of El Centro until the new leveling and the old leveling showed a continuous agreement, within the limit of the errors of the leveling, for a considerable distance. This was done and, after the results of the re-leveling were studied, it was found that, if the new and the old leveling were computed continuously from a common elevation for a single bench-mark in the vicinity of Niland, California, southward to El Centro, and westward to Jacumba, California, and then from El Centro, California, eastward to Yuma, Arizona, that the new and old elevations at both Jacumba, California, and Yuma, Arizona, were in agreement within considerably less than one inch. There were, however, certain places where groups of bench-marks exhibited movement of several times this amount, or about 70 or 80 millimeters.

All of the leveling involved in the original determination of these elevations and in the re-leveling after the earthquake was of first-order accuracy. It was possible, even over the large area involved, to detect and point out with a considerable degree of certainty movement that, in all probability, nowhere exceeded four inches.

Had the leveling involved been of second-order accuracy, the errors of the leveling itself might easily have been large enough to somewhat camouflage the change in elevations of the marks due to the earthquake and it would have been not nearly as safe to say that movement had occurred at certain specific bench-marks as it was with the findings based on first-order leveling. Had the leveling been of third-order accuracy, I doubt very much if the movement would have been detected at all or, if it had shown up in the leveling, it would have been an even chance that the indicated movement was merely an accumulation of error in the leveling itself.

The first-order level-net of the United States is rapidly nearing completion and, in fact, it is probable that before the end of the summer of 1934 the only first-order leveling remaining to be run to complete the 100-mile spacing required of the first-order net will be the rerunning of certain doubtful lines or some old lines which were run, prior to 1900, with instrumental equipment and under instructions which did not yield the accuracy obtainable with the present instrumental equipment and observing program.

This fundamental net of first-order leveling, with lines spaced approximately 100 miles apart, is being broken up by means of second-order lines at 50-mile and 25-mile spacings and should, when it is completed, furnish a most excellent foundation for the determination of Earth-movement by means of re-leveling to be run in the future.

In certain of the regions known to be seismologically active, first-order lines have been run at intervals of less than 100 miles for the special purpose of strengthening the foundation which may at any time be required in connection with re-leveling operations after earthquake-shocks have occurred.

In the Los Angeles Area, the first leveling of high precision was done in 1906, when a line of first-order levels was run from San Diego to Santa Ana and then eastward into the interior. In 1919 and 1920, levels were brought down from San Jose to Santa Ana and from then on, at intervals, throughout the next eight or nine years additional lines of first-order leveling were run, in Los Angeles and the surrounding area, until a net of first-order leveling had been developed covering that area with lines much more closely spaced than the 100 miles required of the fundamental net. Unfortunately, this leveling extended over a long period of years and the closures indicate that there must have been some minor movements which occurred during the period covered by these various leveling-projects, since the closures were, in some cases, considerably larger than might be expected with this class of leveling and the small size of the circuits involved. In the winter of 1931-32, it was decided to relevel the four circuits lying closest to Los Angeles all at one time. A party was placed in the field for this purpose. This re-leveling included the old lines within the area roughly outlined by San Pedro, Santa Monica, Chatsworth, Burbank, Santa Ana, and Long Beach. When the results of this re-leveling were compared with the adjusted results of the previous leveling, which had been run piecemeal, it was found that changes in elevation, to the extent of 70 or 80 millimeters, were indicated in the vicinity of Santa Ana. This being on the very edge of the re-leveling project, it was decided the next winter to carry the re-leveling from Santa Ana on southward to San Diego. This was done with the result that, within a space of slightly more than one year, re-leveling was carried out over all the lines in the area mentioned and along the line from Santa Ana to San Diego, California. This work had just been completed when the Long Beach earthquake of March 1933 occurred, and in the winter of 1933-34 a party was again placed in the field to rerun the various lines of leveling, covering the area surrounding Los Angeles and Long Beach, and to carry the re-leveling far enough away from the center of the disturbance so that it was connected to bench-marks, which, as indicated by a comparison of the new leveling and the old, had remained undisturbed. This leveling has just been completed but the results are not yet available for distribution or discussion since the computation in the office of the new leveling is now being made in New York.

I previously mentioned the re-leveling in the vicinity of El Centro, California, an informal report on which was made to the Carnegie Institution of Washington shortly after the computations and study had been completed. This leveling showed, rather plainly, two disturbed sections of the line, namely, one between Niland and El Centro, and another eastward of El Centro, in such positions that, if a line were drawn between the two portions of the leveling which showed the disturbance, the line would very closely parallel the general trend of the fault-lines in the Southern California Region.

A year or so ago, an earthquake occurred in Nevada, which was heavy enough so that, had it occurred in a well-settled and built-up region, excessive damage to life and property undoubtedly would have occurred. As one of the leveling parties of the Coast and Geodetic Survey was expected to cross that area shortly after the earthquake, it was decided that the leveling in that active area should be specially designed as a foundation for the detection of future movements. This was accomplished by so routing the party that it crossed and re-crossed the existing fault-lines. Wherever faults could be identified, marks were established in pairs on either side so that future leveling might exhibit any movement which took place with a minimum amount of new field-work.

In the area around San Jose, California, the original leveling of 1906 and 1920 and re-leveling in the winters of 1931-32, 1932-33, and in the spring of 1933, has proven Earth-movement, in the area roughly outlined by Redwood City, Niles, and Coyote, which reaches a maximum in the vicinity of San Jose and which has, in the last fifteen years, amounted to 3-1/2 or 4 feet. There is some doubt as to whether this movement is due to seismological activity or whether it is due to excessive drought and excessive pumping and the consequent lowering of the water-table under the region. It is planned to re-level lines in the region around San Jose at frequent intervals for the next few years in an effort to determine more exactly the extent of the affected area and to keep a watch on the future behavior of this most interesting and important area.

Not long ago a considerable amount of detailed leveling was done in the region around New Madrid, Missouri, in an effort to lay a foundation which would be useful in studying the behavior of that region, which, while not recently active, is by some suspected of being a possible source of trouble in the future.

At present we have not much in the way of proven Earth-movements to show for the leveling which has been done in connection with earthquake-investigations. In fact, the results of the re-leveling following the earthquake, which centered around Brawley, California, are the only ones which have been studied and reported on completely. A preliminary report has been published in connection with the settlement around San Jose, California.

The results of the recent re-leveling following the earthquake around Long Beach, California, are now being worked up and it is hoped that we will have some concrete results within a few months.

The most of the activity to date has occurred in laying foundations on which to base future work as earthquakes occur or as re-leveling is run in an effort to detect slow motions which may presage earthquakes. The problem is an extremely large one and at present we have hardly scratched the surface.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE EARTHQUAKE OF SEPTEMBER 6, 1933, AND ITS BEARING ON THE PROBLEM OF THE DEEP EARTHQUAKE

G. J. Brunner, S.J.

The earthquake recorded on September 6, 1933, throughout the world clearly manifested an exceptionally deep origin (Fig. 1).

Quite in accordance with theory, only little of the energy of the disturbance appears in the upper strata as surface-waves. These are either insignificant or absent altogether in a distant quake of moderate intensity whereas in a violent quake of normal depth (12 km) the maximum trace-amplitude of the surface-waves will be 5 to 30 times that of the S-phase (Fig. 2).

Conspicuous are the phases pP and sS whose presence really characterizes a deep-focus disturbance (Fig. 3). The rays FBS_2, consisting of the parts FB and BS_2, are designated pP when both parts are compressional waves and sS when transverse waves. The point of reflection B is close to the epicenter and approaches E with increasing epicentral distance. When the composite ray pP emerges at about 90°, the point B is about 1° from E according to Stechschulte (Fig. 4).

The epicenter as calculated from ten original seismograms and from ten bulletins was found to be 23°.6 north latitude at 178°.8 west longitude, close to the epicenter of May 26, 1932, at a distance of 1°.5; we may consider the second earthquake a repetition of the first. The time of occurrence was $22^h\ 08^m\ 33^s$ on September 6, 1933 (Fig. 5).

Valuable data were gathered concerning the problem of the deep earthquake. Foremost are the time-intervals of pP-P and sS-S (Fig. 6). Beginning probably at about 100° these intervals are constant.

R. Sorase, who studied the quake of February 20, 1931, of 350-km depth, and V. Stechschulte, studying that of March 29, 1928, of 400-km depth, found this constancy to begin, in the case of those earthquakes, already at about 70° epicentral distance. The quake of May 26, 1932, of 570-km depth reached its maximum interval at 83°.

The rays passing through the Earth's core (see Fig. 3) show clearly developed phases P' and pP'. The interval seems to be constant, no matter what the epicentral distance, as we found from 50 original seismograms of the quake of May 26, 1932. Of the present quake the seismogram of Stuttgart (Fig. 7) at $\Delta = 155°$, gives an interval of 144 seconds for (pP' - P').

Assuming the constancy of the (pP' - P') interval, we can readily calculate the depth of focus. The interval will then be the same at the antipodes where one-half of its amount is evidently the time required for the first shock to travel to the nearest point on the Earth's surface, that is, the epicenter.

From the velocity-values recently computed as in Table 1 by C. G. Dahm at the Geophysical Laboratory of Saint Louis University the 72 seconds required for the emergence of the vertical ray will give a depth of 637+ km. As the Earth's radius is 6373 km, the depth of this quake is exactly one-tenth of the radius.

Table 1--Velocities of the P-wave according to C. G. Dahm

Depth	Velocity	Average velocity	Time	Total time
km	km/s	km/s	s	s
0	6.30			
		7.53	13.29	0
100	7.93			
		8.10	12.35	13.29
200	8.28			
		8.49	11.80	25.64
300	8.71			
		8.94	11.20	37.44
400	9.17			
		9.41	10.63	48.64
500	9.64			
		9.87	10.03	59.30
600	10.08			
		10.29	9.72	69.30
700	10.47			

Table 2--Distance-time intervals for earthquake of September 6, 1933

Station	Δ	pP-P	sS-S	S-P
	°	m s	m s	m s
Riverview	28.0	1 38	3 05	4 23
Pasadena	81.3	2 07	3 56	9 14
Berkeley	81.5	2 08	3 57	9 18
Saint Louis	103.0	2 14	4 05	11 00
Cincinnati	108.0	2 13	....	11 34
Georgetown	113.1	2 14	4 04	11 31
Fordham	116.3	....	4 04	11 33

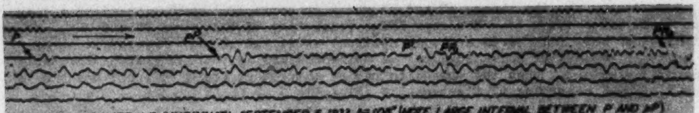


FIG. 1—GALITZIN Z, CINCINNATI, SEPTEMBER 6, 1933, Δ=108° (NOTE LARGE INTERVAL BETWEEN P AND pP)

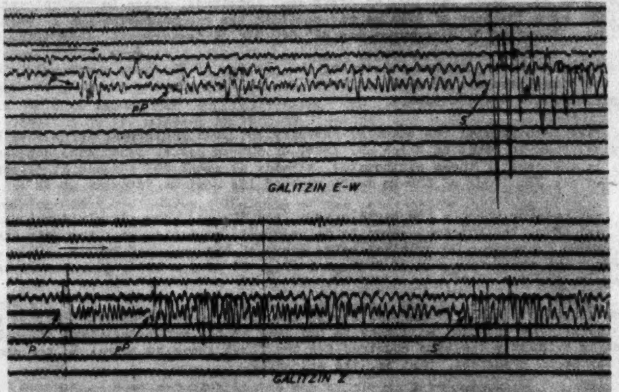


FIG. 2—RECORDS AT BERKELEY, SEPTEMBER 6, 1933 (NOTE THE LARGE P AND pP ON THE Z-COMPONENT, THE LARGE S ON THE E-W-COMPONENT, AND THE ABSENCE OF SURFACE-WAVES)

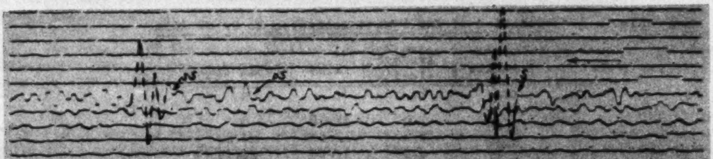


FIG. 3—GALITZIN N-S, FLORISSANT, SEPTEMBER 6, 1933 (NOTE LARGE AMPLITUDES OF S AND sS AND ABSENCE OF SURFACE-WAVES)

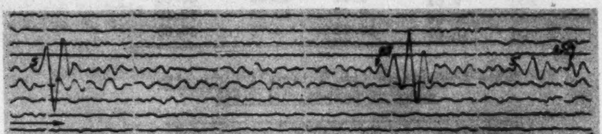


FIG. 6—GALITZIN N-S, FORDHAM, SEPTEMBER 6, 1933, Δ=115°.3 (NOTE LARGE INTERVAL BETWEEN S AND sS)

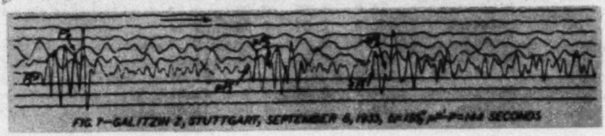
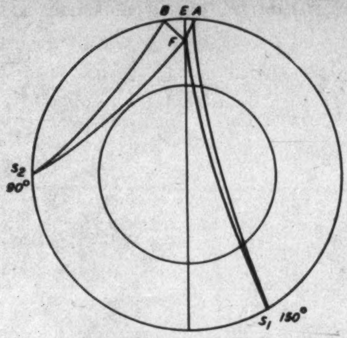


FIG. 7—GALITZIN Z, STUTTGART, SEPTEMBER 6, 1933, Δ=155°, pP'–P'=144 SECONDS


B
E
A
F
S2
90°
S1 150°

PATHS OF RAYS, AFTER STECHSCHULTE

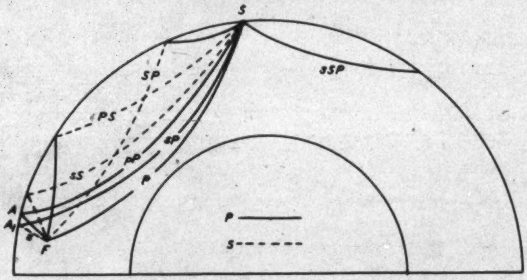

S
SP
sSP
PS
SP
SS
PP
P
A
A1
F
P
S

FIG. 4—PATHS OF RAYS, AFTER F.J. SCRASE

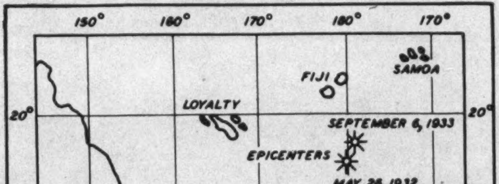

150°
160°
170°
180°
170°
SAMOA
FIJI
LOYALTY
20°
20°
SEPTEMBER 6, 1933
EPICENTERS
MAY 26, 1932
AUSTRALIA
30°
30°
KERMADEC ISLANDS
NEW ZEALAND
40°
40°
150°
160°
170°
180°
170°

FIG. 5—EPICENTERS OF THE DEEP-FOCUS EARTHQUAKES OF MAY 26, 1932, AND SEPTEMBER 6, 1933

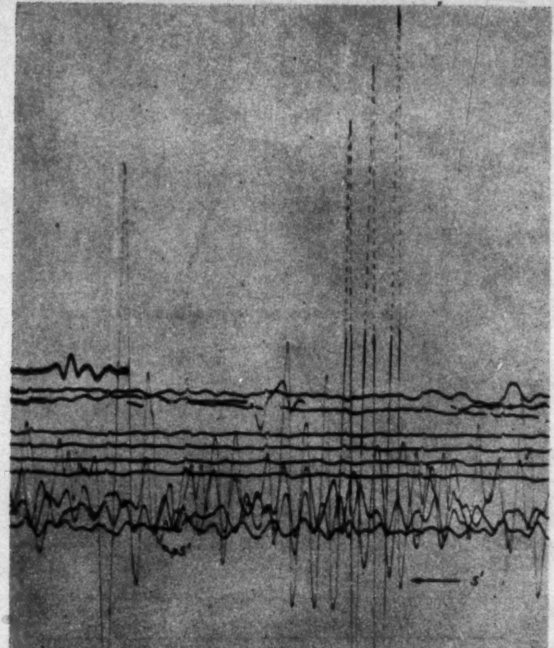


FIG. 8—GALITZIN Z, GEORGETOWN, MAY 26, 1932, Δ=115.3 (NOTE THE ENORMOUS S'-PHASE)

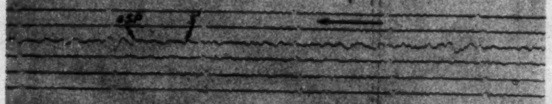


FIG. 9—GALITZIN E-W, SEPTEMBER 6, 1932 (S' IS ALMOST ABSENT)

A major point of inquiry in this earthquake was the presence or absence of S', the transverse-wave through the Earth's core. This wave stands out most conspicuously in the earthquake of May 26, 1932, where on twelve original seismograms from 105° to

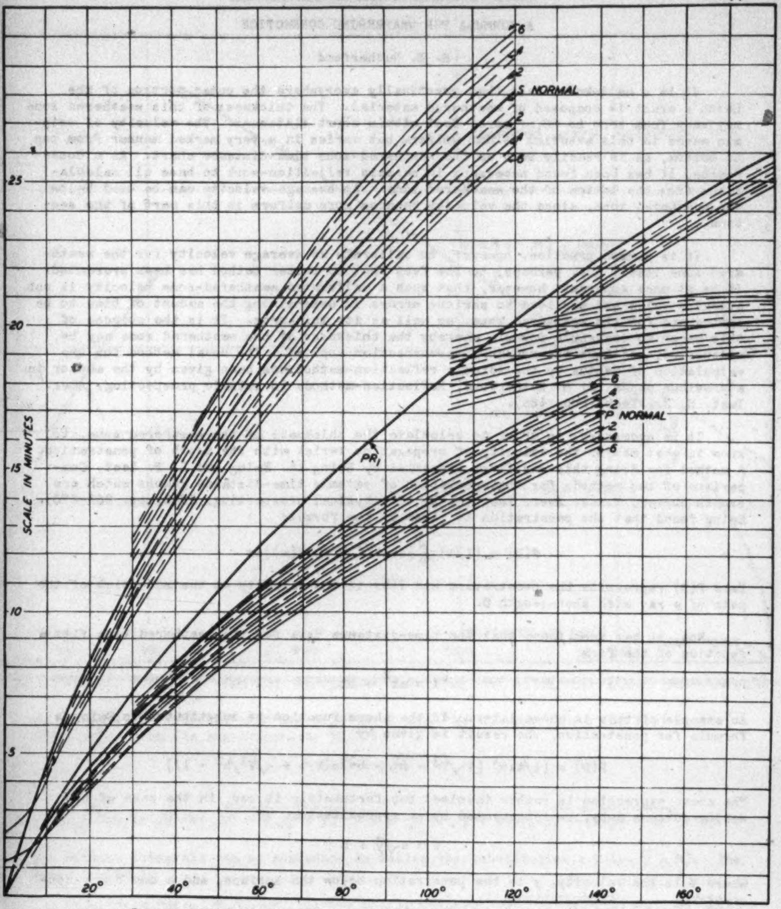


FIG. 10—DEPTH-TIME VERSUS DISTANCE OF DEEP EARTHQUAKES

120° it has the largest trace amplitude on each record (Fig. 8). The seismograms of September 6, 1933, show very little of it (Fig. 9).

Here we are confronted with a real problem: Why is S' so abnormally developed in one quake and nearly absent in the second, from practically the same locality?

The quake of September 6, 1933, has contributed to the development of the depth-chart and will help toward the solution of the problem of deep-focus earthquakes (Fig. 10).

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A FORMULA FOR WEATHERING CORRECTION

H. M. Rutherford

It is a well-known fact that practically everywhere the outer portion of the Earth's crust is composed of weathered material. The thickness of this weathered zone may vary from zero to 50,or more, feet within short distances. The velocity of seismic waves in this material is not uniform but varies in a very marked manner from top to bottom, as is readily seen on the weathered-zone time-distance chart. As a consequence, it has been found necessary in seismic reflection-work to base all calculations from the bottom of the weathered zone. An average velocity can be used below the weathered zone, since the velocity becomes more uniform in this part of the section.

It is common practice, however, to calibrate an average velocity for the weathered zone itself due, perhaps, to the fact that no better method has been presented. It is at once apparent, however, that such a calibrated weathered-zone velocity is not actually valid and may lead to serious errors in determining the amount of time to be subtracted for the weathered zone, as well as its thickness. It is the purpose of this paper to present a formula whereby the thickness of the weathered zone may be calculated, and thus the proper time-correction applied. The usual method for the calculation of depths by the seismic reflection-method has been given by the author in a previous paper (H. M. Rutherford, Reflection-methods in seismic prospecting, Amer. Inst. M. E., Tech. Pub. 486).

It is necessary, in order to calculate the thickness of the weathered zone, to know in what manner the velocity of propagation varies with the depth of penetration. A method for doing this was first presented by Ewing (M. Ewing and L. D. Leet, Comparison of two methods for interpretation of seismic time-distance graphs which are smooth curves, Trans. Amer. Inst. M. E., Geophysical prospecting, 1932, pp. 263-270). Ewing found that the penetration is given by the formula

$$P(D) = (1/\pi) \int_0^D [\cosh^{-1} V(D)/V(x)]dx$$

Here P(D) represents the penetration and V(D) is the velocity at the mid-point of the path of a ray with shot-length D.

Now, it has been found that the time-distance data for the weathered zone fits a function of the form

$$X = at^2 + bt$$

An example of this is shown later. If the above function be substituted in Ewing's formula for penetration, the result is given by

$$P(D) = (1/4a\pi) [V\sqrt{V^2 - b^2} - b^2\ln(V/b + \sqrt{V^2/b^2 - 1})]$$

The above expression is rather involved but fortunately it can, in the case of the weathered-zone data, be represented by an approximation, or

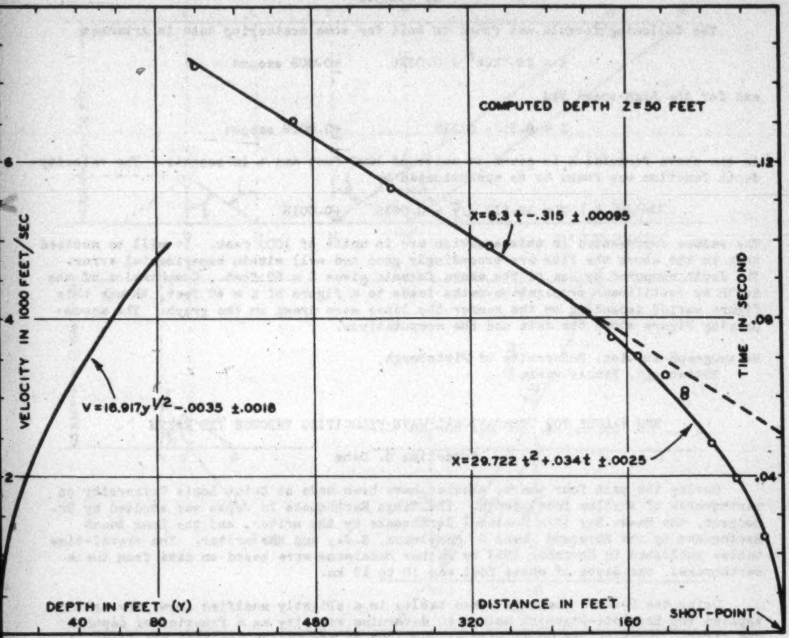
$$V = a\sqrt{y} + b$$

where V is the velocity, y is the penetration below the surface, and a and b are constants.

The author has shown that the time-distance relationships for the case of a high-velocity bed whose overburden consists of material in which the velocity is a steadily increasing function of the depth is given by (H. M. Rutherford, Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 289-303)

$$t = 2 \int_0^Z Vdy/[V(y)\sqrt{V^2 - V^2(y)}] - (2/V) \int_0^Z V(y)dy/\sqrt{V^2 - V^2(y)} + D/V$$

where Z is the depth of the high-speed bed below the surface, or the thickness of the overburden, V is the velocity of the high-speed bed, V(y) is the velocity-depth function, and t and D are the time and horizontal distance on the surface for any ray



A TYPICAL PROFILE WHICH PENETRATES THE WEATHERED ZONE (ARKANSAS)

which has been refracted over the high-speed bed. We now substitute for $V(y)$ in the above expression its approximation, that is

$$V(y) = a\sqrt{y} + b$$

and get

$$t = 2\int_0^Z Vdy/(a\sqrt{y}+b)\sqrt{V^2-(a\sqrt{y}+b)^2} - 2/V \int_0^Z (a\sqrt{y}+b)dy/\sqrt{V^2-(a\sqrt{y}+b)^2} + D/V$$

The various integrals can be evaluated by making the substitution $u = (a\sqrt{y} + b)$. The final result is

$$\begin{aligned} t = {} & (4V/a^2)\{\sin^{-1}[(a\sqrt{Z}+b)/V] - \sin^{-1}(b/V) + (b/V)\ln[(V+\sqrt{V^2-(a\sqrt{y}+b)^2}]/(V+\sqrt{V^2-b^2})\} \\ & - (4/a^2V)\{[(V^2/2)\sin^{-1}[(a\sqrt{Z}+b)/V] + [(b-a\sqrt{Z})/2]\sqrt{V^2-(a\sqrt{Z}+b)^2}] \\ & - [(V^2/2)\sin^{-1}(b/V) + (b/V)\sqrt{V^2-b^2}]\} + D/V \end{aligned}$$

The above formula is general and holds for depths for any high-speed bed if the overburden has a velocity-depth function of the form given. The formula for the case of reflections is given in its parametric form by merely substituting for V the parameter K, and writing the corresponding formulas for time and distance.

An example

The following formula was found to hold for some weathering data in Arkansas

$$X = 29.722t^2 + 0.039t \qquad \pm 0.002 \text{ second}$$

and for the high-speed bed

$$X = 6.3t - 0.315 \qquad \pm 0.0009 \text{ second}$$

In the above formulas X is given in units of 1000 feet and t in seconds. The velocity-depth function was found to be approximated by

$$V = 16.917 \sqrt{y} - 0.0035 \qquad \pm 0.0018$$

The values represented in this equation are in units of 1000 feet. It will be noticed that in the above the fits are exceedingly good and well within experimental error. The depth computed by use of the above formula gives Z = 50 feet. Computation of the depth by rectilinear propagation-paths leads to a figure of Z = 40 feet, though this figure varied depending on the manner the lines were drawn on the graph. The accompanying Figure shows the data and the computations.

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NEW VALUES FOR DILATATIONAL WAVE-VELOCITIES THROUGH THE EARTH

Cornelius G. Dahm

During the past four years, studies have been made at Saint Louis University on earthquakes of shallow focal depth. The Tango Earthquake in Japan was studied by Dr. Hodgson, the Hawke Bay (New Zealand) Earthquake by the writer, and the Long Beach Earthquake by the Reverend James B. Macelwane, S.J., and the writer. The travel-time tables published in November 1933 by Father Macelwane were based on data from these earthquakes, the depth of whose foci was 10 to 12 km.

Using the P-curve found in these tables in a slightly modified form, the writer applied the Herglotz-Wiechert method to determine velocity as a function of depth in the Earth. Three of the underlying assumptions of the method are that the focus lies in the surface, that all the rays start from that point, and that they are continuous curves and have continuous derivatives. These assumptions can be satisfied by stripping the Earth to the Mohorovicic discontinuity and shifting the rays bodily and without distortion so that they all start from the center of the base of the cone of energy through which they enter the medium below the discontinuity. The depth of the Mohorovicic discontinuity was found by Hodgson to lie at a depth of 16 km in Japan.

It was, therefore, decided to strip the Earth to that depth and to adjust the P-curve to fit a hypothetical Earth in which the medium below the Mohorovicic discontinuity is continuous to the stripped surface.

In order to accomplish this, it is necessary to adjust the travel-times as well as the distances. For all those seismic rays which emerge within the range of a linear travel-time curve, that is, within a few hundred kilometers of the epicenter, the paths in the upper layer are constant, as shown in Figure 1, and are determined by the critical angle, $i = \arcsin (6.3/7.7476) = 54^\circ 24' 19''$. For these rays, therefore, the adjustments of time and of distance are constant, the adjustment in time being $[(4 + 16)/6.3 \cos i]$ seconds, and the adjustment in arcual distance being $[(4 \tan i + 16 \tan i)/111.1]$ degrees.

For those rays which emerge beyond the range of the linear travel-time curve, the corrections vary with the distance of the point of emergence and with the angle of incidence at the surface. Furthermore, the true structure at the observing points must be taken into account. An average structure was postulated for the continents of America, Europe, and Asia, where the majority of the observing stations are located.

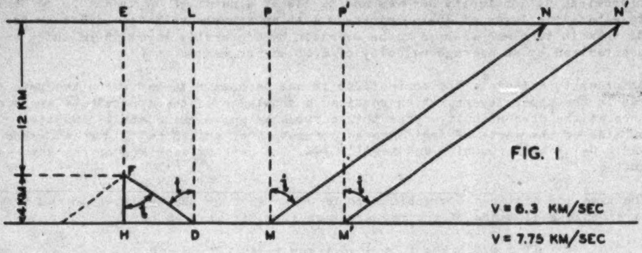
E
L
P
P'
N
N'
12 KM
4 KM
F
i
H
D
M
M'
V = 6.3 KM/SEC
V = 7.75 KM/SEC

FIG. 1

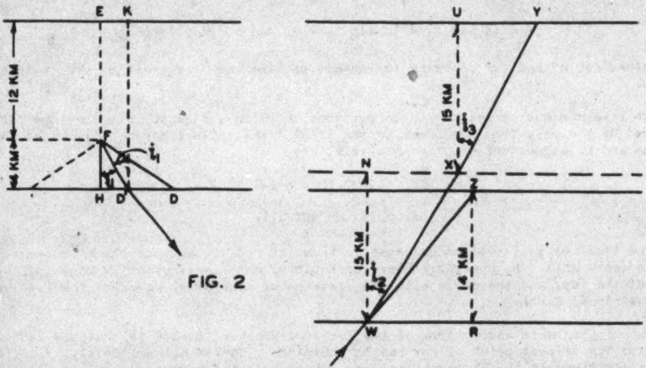
E
K
12 KM
4 KM
F
i_1
H
D
D
U
Y
15 KM
i_3
N
X
Z
15 KM
i_2
14 KM
W
R

FIG. 2

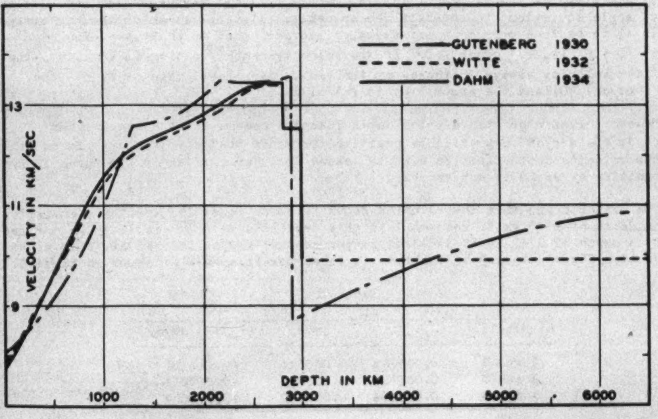

FIG. 3—P-VELOCITY AS A FUNCTION OF DEPTH

The Mohorovicic discontinuity was assumed to lie at a depth of 30 km and to be overlain by a basaltic layer of 15-km thickness with an average velocity of 6.4 km per second; this in turn was assumed to be overlain by a granitic layer 15-km thick and to be characterized by an average velocity of 5.55 km per second.

In order to calculate the corrections it was necessary to determine the path of each ray in the upper layers, which required a knowledge of the approximate angle of incidence at the discontinuity. For this purpose an approximate sin i_Δ function, that is, the sine of the angle of incidence as a function of epicentral distance, was constructed. Using this function and Snell's law, the path at each end of the ray was constructed.

The time and distance corrections to be deducted from the travel-time and from the corresponding distance of any ray are seen from Figure 2 to be

$$dT = 4/6.3 \cos i_1 + 15/6.4 \cos i_2 + 15/5.55 \cos i_3$$

$$d\Delta = (4 \tan i_1 + 15 \tan i_2 + 15 \tan i_3)/111.1$$

the values for dT and for dΔ being in seconds of time and in degrees of arc, respectively.

We have now but to add proper corrections to build up the structure at the further end of the rays from the 30-km to the 16-km level. These corrections in seconds of time and in degrees of arc, respectively, are

$$dT_1 = 14/7.75 \cos NWZ$$

$$d\Delta_1 = 14 \tan NWZ/111.1$$

The time-correction to be deducted is then $(dT - dT_1)$, and the distance correction is $(d\Delta - d\Delta_1)$. By applying these corrections, which vary with the angle of incidence of the ray, and therefore with the distance of emergence, we adapt the P-curve to the stripped Earth.

One of the basic assumptions of the Herglotz-Wiechert method is that the radius-vector to the deepest point of any ray be a minimum. Stated mathematically, $r = f(\theta)$ must be a minimum at the vertex of any ray, where r is the radius-vector and θ is the central angle equivalent to one-half the epicentral distance at which the ray emerges. If this is to be true $d^2r/d\theta^2 = (r^2/v_r)(v_r/r - dv/dr)$ must be positive. Now $d^2r/d\theta^2 > 0$ if $(v_r/r - dv/dr) > 0$. If the velocity-depth function is monotone, that is, if the velocity always increases as the radius decreases, then $dv/dr < 0$ and $(v_r/r - dv/dr) > 0$, and the assumption is fulfilled.

However, even when the velocity-depth function ceases to be monotone, that is, when $dv/dr > 0$, $d^2r/d\theta^2$ may still be positive, provided that $v_r/r > dv/dr$. To determine this the velocity-depth function must be tested for that portion of the curve in which the condition $dv/dr < 0$ is not verified.

The writer found that the velocity-depth function loses its monotonic character after a depth of 2730 km is reached. At this depth the velocity is 13.45 km per second, at a depth of 2769 km it is 13.43 km per second, and at 2780 km it is 13.42 km per second. These data may be combined in three possible ways as shown in Table 1.

Table 1

Combination	v_r/r	dv/dr	$(v_r/r - dv/dr)$
1 and 2	0.003694	0.000513	+0.003181
2 and 3	0.003726	0.000909	+0.002817
1 and 3	0.003694	0.000600	+0.003094

Hence $d^2r/d\theta^2$ is still positive, and the assumption that $r = f(\theta)$ is a minimum at the vertex of the ray is fulfilled.

The Herglotz-Wiechert method could not be applied at depths greater than 2780 km because this was the vertex-depth of the ray which emerged at the epicentral distance 102°.5 and beyond which distance the method is no longer valid, since the travel-time curve loses its concavity to the distances axis and becomes linear. Therefore, in order to extend the velocity-depth function beyond this depth a different method had to be devised. The travel times of P_cP, the dilatational wave reflected from the core of the Earth, were compared with twice the travel-time of P to a depth of 2780 km. By means of this comparison and by means of the slope of the straight-line portion of the P-curve beyond 102°.5, the velocity from 2780 km to the depth of the core was found to have a constant value of 12.57 km per second. The average velocity through the Earth's core is 9.88 km per second.

Table 2--The velocity-depth function in the Earth

Depth	Velocity	Depth	Velocity
km	km/sec	km	km/sec
16	7.75	1600	12.45
100	7.93	1700	12.53
200	8.29	1800	12.63
300	8.71	1900	12.73
400	9.18	2000	12.84
500	9.65	2100	12.95
600	10.09	2200	13.07
700	10.49	2300	13.20
800	10.88	2400	13.31
900	11.26	2500	13.38
1000	11.60	2600	13.43
1100	11.84	2700	13.45
1200	12.03	2800	12.57
1300	12.16	2900	12.57
1400	12.27	<3000	12.57
1500	12.36	3000 to 6371	9.88 average

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THE BAY OF ACAPULCO AND ITS RELATION TO THE EARTHQUAKES IN THE SOUTHERN PART OF THE MEXICAN REPUBLIC

Pedro C. Sánchez

(Translated by Dr. J. L. Thomas)

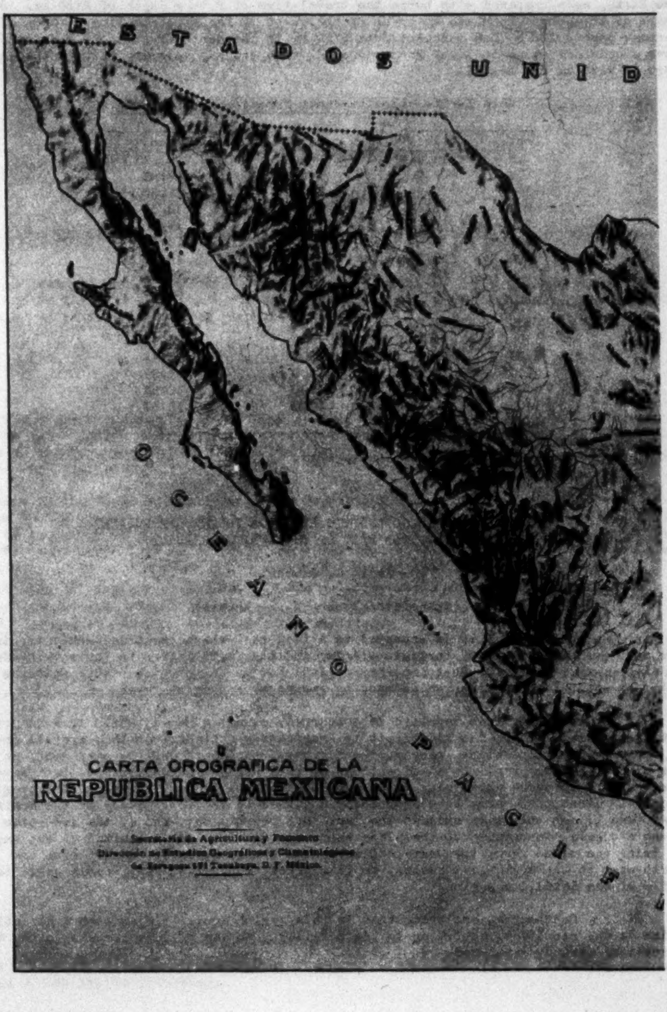
At the present time it is accepted as a fact that the terrestrial mould is, in its most essential part, of tectonic origin, and its modification is the work of denudation, water being its most important agent; but in its characteristic features one notes structural influences, which must be sought in geological ages.

As far as the Mexican Republic is concerned, studying Map 1, which is a diagrammatic representation of the ridges, it is immediately noticed that they are all grouped in two principal directions, namely, the northwest-southeast and the east-west, which are undoubtedly the fundamental directions of the barriers which acted as buttresses during the Cretaceous upheaval. It is evident that the present shapes of the crests, and their directions, have been profoundly modified by erosion. Study of the drainage-plan (Map 1) can only make evident the fact just pointed out, and at the same time gives a special importance to the place where the Santiago and Mezquital rivers empty, as being the place where the Western Sierra Madres end, where the thrust from the north-west to the south-east ceases, to give place to the east-west trends characteristic of the Antillian Region.

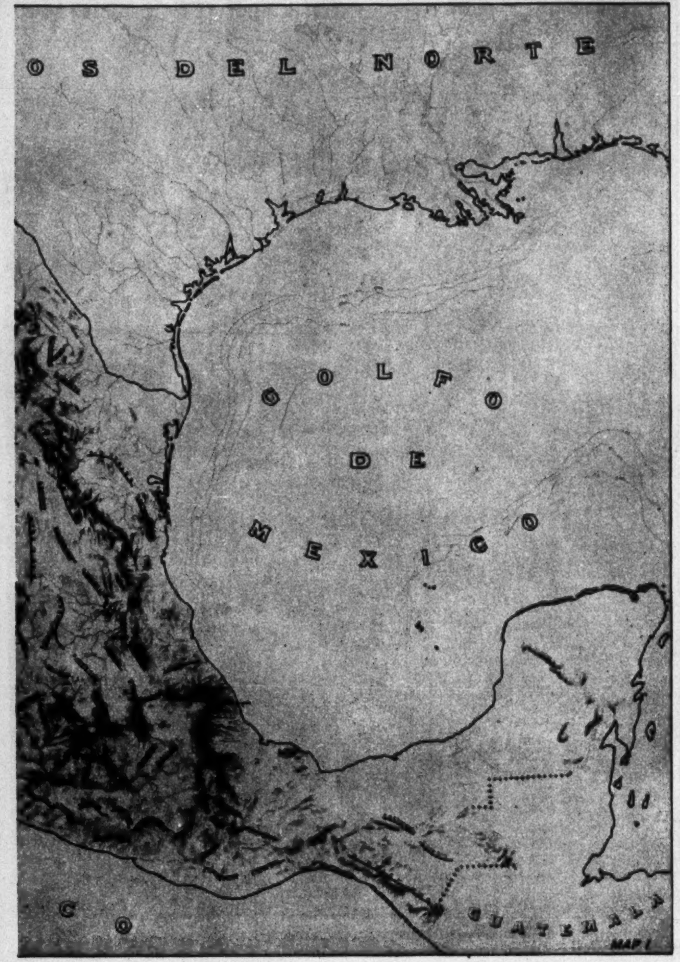
It is a fact worth mentioning that in this region appear ridges with a direction which is the resultant, according to the parallelogram law of forces, between the two directions already mentioned.

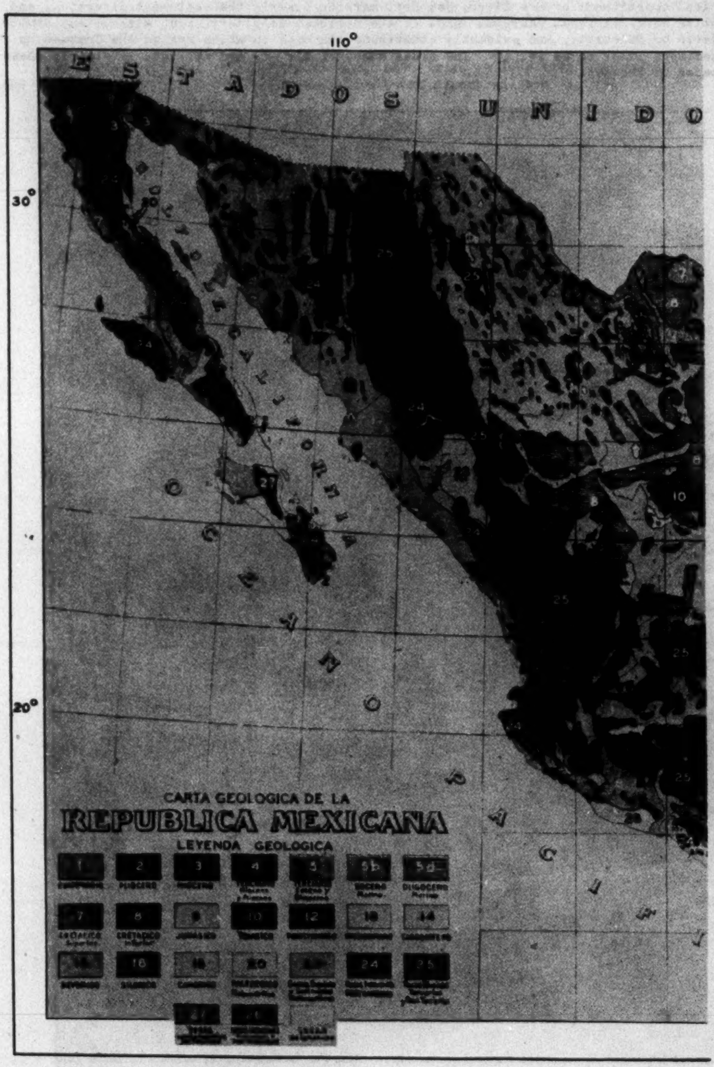
If this Map is superimposed on Map 2--which is reproduced from the geological map of the Republic of Mexico, prepared by the National Geological Institute--a comparative study of the two yields the following deductions:

The intrusive rocks of Lower California, which rise at intervals lengthwise of the Pacific coast, aligned in a northwest-southeast direction, and the gneiss, prin-


ESTADOS UNID
OCEANO PACIFI
CARTA OROGRAFICA DE LA
REPUBLICA MEXICANA
Secretaría de Agricultura y Fomento
Dirección de Estudios Geográficos y Climatológicos
Av. Zaragoza 151 Tacubaya, D. F. México

cipal constituent of the Sierra del Sur, marking clearly the east-west direction, and which were the first emergent lands of the national territory, are, without any doubt, Azoic or Paleozoic, and evidently constitute the base on which rested the Cretaceous sediment later to be folded. The areas numbered 23, 24, and 26 indicate clearly these bases on the map.


OS DEL NORTE
GOLFO DE MEXICO
GUATEMALA
CO
MAP I


110°
30°
20°
ESTADOS UNIDOS
GOLFO DE CALIFORNIA
OCEANO
PACIFICO
CARTA GEOLOGICA DE LA
REPUBLICA MEXICANA
LEYENDA GEOLOGICA
1
2
PLIOCENO
3
MIOCENO
4
5
5b
EOCENO Marino
5d
OLIGOCENO Marino
7
CRETACICO Superior
8
CRETACICO Inferior
JURASICO
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TRIASICO
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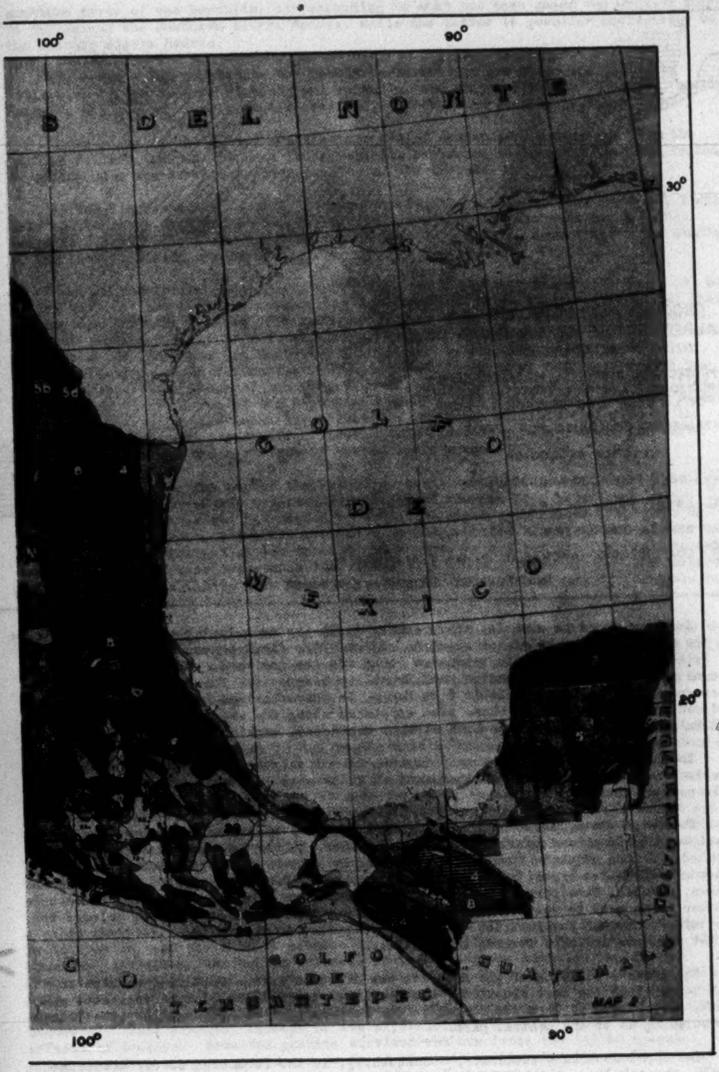
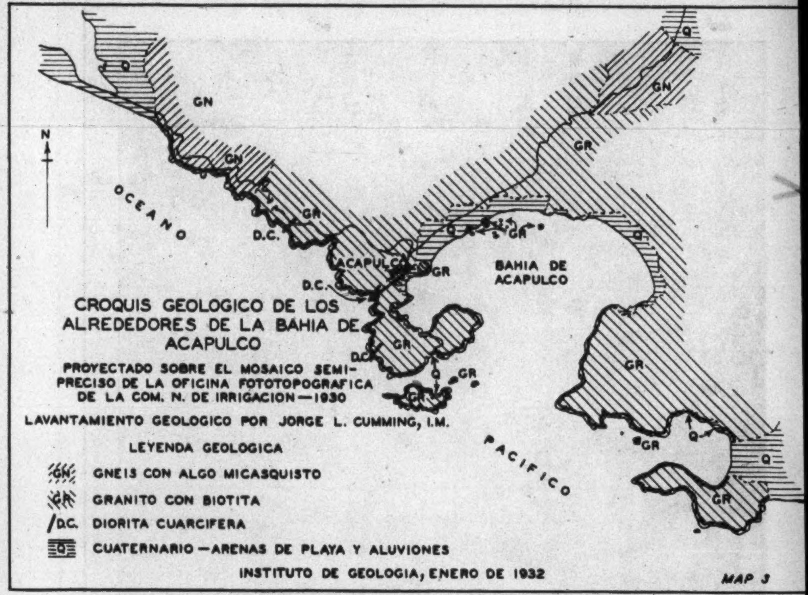

100°
90°
S DEL NORTE
30°
GOLFO
DE
MEXICO
20°
GOLFO
DE
TEHUANTEPEC
GUATEMALA
MAP 2
100°
90°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OCEANO
N
ACAPULCO
D.C.
D.C.
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GR
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BAHIA DE ACAPULCO
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PACIFICO
CROQUIS GEOLOGICO DE LOS ALREDEDORES DE LA BAHIA DE ACAPULCO
PROYECTADO SOBRE EL MOSAICO SEMI-PRECISO DE LA OFICINA FOTOTOPOGRAFICA DE LA COM. N. DE IRRIGACION—1930
LAVANTAMIENTO GEOLOGICO POR JORGE L. CUMMING, I.M.
LEYENDA GEOLOGICA
GN GNEIS CON ALGO MICASQUISTO
GR GRANITO CON BIOTITA
D.C. DIORITA CUARCIFERA
Q CUATERNARIO—ARENAS DE PLAYA Y ALUVIONES
INSTITUTO DE GEOLOGIA, ENERO DE 1932

MAP 3

Studying Map 2 as a whole, there appear in it the principal phases of the features of the constituent rocks of our mountain chains. The first phase--the oldest, Azoic or Paleozoic--consists of the intrusive rocks and the gneisses, probably of the same age as the Scandinavian, Canadian, and Brazilian basements. The second phase, which corresponds to the areas numbered 8 on Map 2, is characterized by a predominance of sediment of the Cretaceous, whose seas stretched along the shores of the various Azoic and Paleozoic islands which we have already mentioned, marking their outlines on them.

The Cretaceous margins are very important, not only in Mexico but in all of North America; thus it is that the predominance of these seas is a most notable feature in this part of the Continent.

The third phase, shown by areas numbered 1 on Map 2, is the effusion of andesite, trachyte, rhyolite, and basalt across the crevices, in the two directions already indicated, or from volcanic openings, as is clearly seen in the region where principal volcanoes of Mexico are aligned, namely, Citlatepetl, Popocatepetl, Ajusco, Nevado de Toluca, Jorullo, Tancítaro, and Colima, whose eruptions have been following one another in an east to west direction in such a way that the last activity belongs to the volcano nearest the Pacific, just as has happened in Central America, indicating a thrust from the Atlantic towards the Pacific.

The present moulding of the Republic was effected in the Tertiary, perhaps in its last part, since the last eruptions, the result of the folding of the Cretaceous sediments, contributed to form the ranges in the western part and to construct the principal building up of the central part.

Two architectures predominate, consequently, in the formation of our mountains, namely, the tabular and the folded. The former is peculiar to the western and the southern parts of the Republic, corresponding to what has been named the Western Sierra Madres and the Southern Sierra Madres, while the latter is peculiar exclusively to the Eastern Sierra Madres.

The rocks which constitute the tabular architecture are those designated by geologists by the name of plutonic and volcanic, and they are always in masses, mostly compact, and more or less pseudo-stratified, or rather in successive flows.

Those rocks of the folded architecture are of sedimentary origin and form the highest reliefs, and as its name indicates, its peaks are variously tilted and folded, depending upon the direction and intensity of the thrusts.

Having discussed the general ideas concerning the orogeny of the Republic, I will take up the range that formed the Bay of Acapulco, which is shown on Map 3. This range is almost elliptical, and its constitution is granitic, according to the studies of the National Institute of Geology.

Mexican and foreign geologists agree in considering that the Sierra Madre del Sur is the best-defined tectonic unit of the Republic, and to me it is the principal basis of the view that the folding of the Cretaceous has caused the Western Sierra Madres. The most important fault of such a folding facilitated the escape of the lava from the volcanic cones (from the San Martín Tuxtla Volcano in the Gulf of Mexico to Colima near the Pacific, which define the fault), present location of the range called the "Volcanic axis"--the cause of the formation of the tectonic trenches, in which flow the most important rivers of the Republic. These rivers are in the south (the Balsas River), in the north (the Lerma River), and in the north slightly dislodged by the eruptions of Ceboruco, the Santiago River, which flows from Lake Chapala and whose axis clearly defines the direction of the tectonic trench.

As is seen from the map of the Republic, the Acapulco Range has constituted an obstacle to the flow of the waters which descended the southern water-shed of the Southern Sierra Madres and has caused them to flow towards the lakes or lagoons of Papagayo and of Coyuca, which are separated by the Acapulco Range and which reach to its sides. The principal rivers through which these waters run are the Papagayo and the Coyuca, and of less importance the Aguacatillo and the Ejido Viejo. The Acapulco Range has an area slightly less than 140 square kilometers, and some of its peaks reach to heights of about 900 meters.

The effects of erosion are not clearly marked, as the flow of the water from the rains takes place through poorly defined channels, which makes one suppose that this Range is very recent, since the canyons of the Southern Sierra Madres, composed of granites and of gneisses, are deep and the effects of a very strong erosion are seen throughout the entire length of these canyons.

This is made clear because the author believes the Sierra de Acapulco, of small size and of recent formation, is due to a granitic intrusion. Such intrusion from an interior magma is rather common. The author has encountered in Oaxaca intrusive granitic rock forming small ridges, like the Yalaleg, in which the stratification shows that they are later than the effused Tertiary, andesite, rhyolite, dacite, and trachyte, which are predominant in those localities and in which there does not exist the slightest vestige of recent volcanic activity. This has suggested to the author the idea of connecting the granitic intrusions with the strong earthquakes throughout all of the Republic south of the volcanic axis, which constitutes the northern limit of the region of strong seismic activity of the Republic of Mexico, according to the studies of the National Geological Institute.

In the opinion of Mr. de Lapparent, the exposure of the granitic rock is due only to erosion, and the intense erosion of the Sierra Madre del Sur corroborates this opinion. Therefore, the writer believes that the ridge of Acapulco is due to a granitic intrusion, which was covered by sedimentary strata of the Cretaceous, which once removed by erosion facilitated the arching in this region due to the injection of the internal magma. This arching would hasten erosion, which at last left the granite uncovered. This granite, because of its crystalline structure, better resisted the effects of erosion. Thus the granite survived and now forms the Bay of Acapulco, which therefore must be considered to be of tectonic origin, and its mould must be due almost entirely to denudation and to the effect of the waves.

The geologist Cumming, who made a geological study of the region of the Acapulco, sent by the Geological Institute at the request of the Pan American Institute of Geography and History, says in his report that "The mountainous mass which surrounds Acapulco ends on the north in a level plot called 'La Sabana' which is bordered on the west by a hilly region, at the continuation of which appear the first counterforts of the Southern Sierra Madres." That is to say, he considers the Ridge of Acapulco to be independent of the Southern Sierra Madres, and the writer is of the same opinion.

Cumming also, on studying the physiography of the region, says: "The area, in spite of being rugged in the neighborhood of the Bay of Acapulco, has the appearance of having been subject to denudation for an extremely long time, so that the intrusive rocks, of a relatively deep consolidation, have been brought into view." Thus he accepts the Ridge of Acapulco as intrusive and its appearance as due to erosion.

Again Cumming says that "In spite of the fact that all of the physiographic characteristics seem to indicate a coast of submergence, there is one fact that indicates a very recent small emergent movement, which appears not to have modified the general characteristics already cited. On the beach of Caleta, south of the town of Acapulco, is found a small bank of madrepores mixed with sand, poorly consolidated, which undoubtedly was formed under the water and which is at present at the height of high-tide, remaining out of the water almost all the time. I think it hardly probable that a storm of exceptional intensity has thrown this bank out of the water, but that it is really an indication of a recent very small emergence."

According to the data gathered by the writer in company with engineer Octavio Bustamante, who accompanied him during the exploration of the Bay of Acapulco, the place now occupied by the Hotel Hornos, was a mound of madrepores, and for this reason the emergence of which Cumming speaks must have been of considerable importance, and the writer connects it with the injection of the granitic mass.

For the purpose of this study, the writer regards it as unimportant whether or not the coast is one of submergence or of emergence. It only seems essential that geologists admit that there has been emergence, even though it be in a small area (the region occupied by the Ridge of Acapulco contains scarcely 140 square kilometers), and that the said mass be intrusive.

The geologist Hisazumi, employed by the National Geological Institute, who visited Acapulco and studied the State of Guerrero before Cumming, says in his report (edited and adopted by the author for the Institute): "The principal topographic form of the region is evidently the result of tectonic conditions,especially in the mountainous region where are reflected the diastrophic movements, modified later by strong erosion." And further on he says: "Among the secondary aspects of the region the coastal features show something interesting, as in several places are found sand-banks away from the beach. This kind of development of the coast indicates that the region was elevated, the submarine bars remaining above the beach. The most notable case of this kind may be found between the towns of Pié de la Cuesta and San Jerónimo, of some 60 kilometers in length and from 30 to 1200 meters wide. When one investigates the entire coast-line of the Costa Grande, one agrees that it is typical of continuous submersion, having had, nevertheless, a small very recent elevation, as is demonstrated by the elevated sand-bars--not very high--along the coast."

In Hisazumi's report previously cited, he states further "The outcroppings of augite schists are very small and have been profoundly influenced by igneous intrusions. The striped appearance of this rock is probably due to these intrusions."

Hisazumi accepts the existence of the intrusive masses as the cause of the metamorphosis of other rock.

From what has already been stated the author believes himself to be correct in claiming that the Bay of Acapulco is of tectonic origin, formed by an intruded mass of granite and moulded by erosion and waves, and probably the epeirogenic movements have helped facilitate the action of the waves and the other agents of erosion.

I do not know whether or not in other regions the granitic intrusions are intimately connected with seismic phenomena, but in the southern region of the Republic of Mexico there does not remain the least doubt.

Dirección de Estúdios Geográficos y Climatólogicos,
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SEISMOLOGICAL OBSERVATIONS ON QUARRY-BLASTING

Maurice Ewing, A. P. Crary, and J. M. Lohse

The work reported here represents the first step in a seismological investigation which may be considered as intermediate between seismic prospecting and the study of earthquakes. The vibrations studied were from blasts in limestone-quarries operated by cement and crushed-stone manufacturers. These vibrations have been recorded at distances ranging up to 13 miles. Most of the observations have been taken in Lehigh and Northampton counties in eastern Pennsylvania.

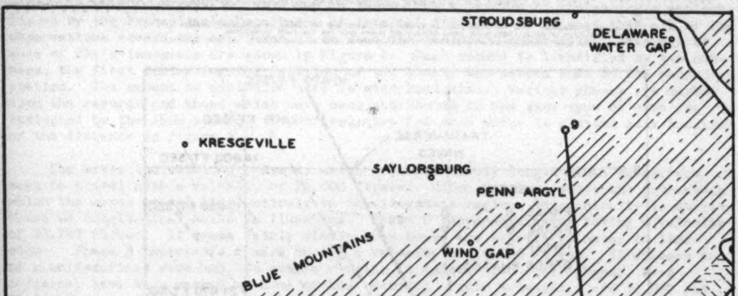

STROUDSBURG
DELAWARE WATER GAP
9
KRESGEVILLE
SAYLORSBURG
PENN ARGYL
BLUE MOUNTAINS
WIND GAP
PALMERTON
BELFAST
8
NAZARETH
5
6
BATH
7
3
4
2
EASTON
DELAWARE RIVER
NEW JERSEY
1
BETHLEHEM
ALLENTOWN
LEHIGH RIVER

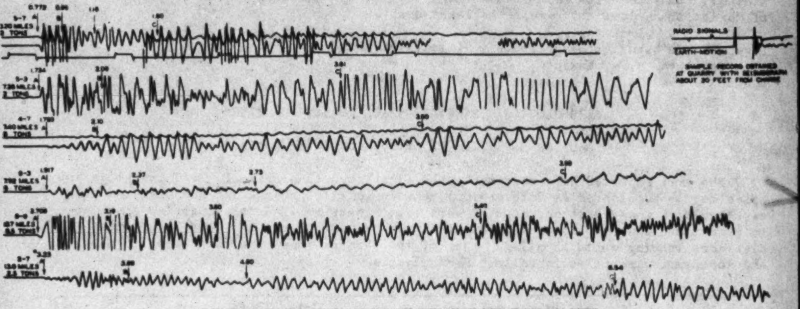
FIG. 1—MAP SHOWING LOCATION OF BLASTS AND RECORDING STATIONS

LEGEND

▨ BEEKMANTOWN LIMESTONE

- - - - LEESPORT CEMENT ROCK

▨ MARTINSBURG SHALE



ON ALL SEISMOGRAMS THERE ARE TIMING-LINES 0.01 SECOND APART, WHICH ARE NOT SHOWN, AS ALSO RADIO SIGNALS FOR CORRELATION OF TIMING-LINES; THESE RADIO SIGNALS ARE SHOWN ONLY FOR THE FIRST SEISMOGRAM

*INSTANT OF BLAST UNKNOWN; THIS PHASE ASSUMED TO BE LONGITUDINAL WAVE OF SAME VELOCITY AS OTHER A-PHASES

FIG. 2

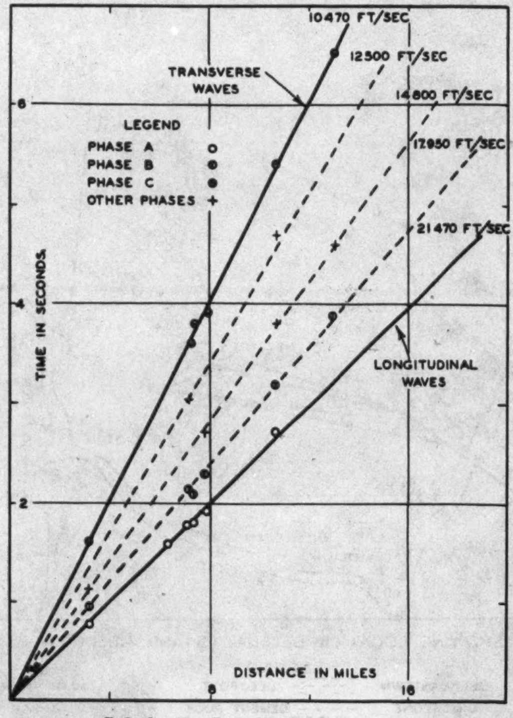


FIG. 3—TIME-DISTANCE CURVES

Apparatus--The seismograph used is of the type known technically as a geophone. Its magnification varied from approximately 400,000 to 100,000 in the range from 70 cycles to 30 cycles. Only the vertical component of motion was measured. In each case a recording location was chosen at a suitable distance from the quarry in a region comparatively free from local disturbances. The geophone was usually buried a few feet underground to avoid effects of the wind.

A low-sensitivity seismograph placed at the quarry was used to record the exact instant of the blast. Tuning forks at each seismograph placed time-marks upon the records at intervals of 0.01 second, and signals from a radio transmitter which were recorded on both seismograms served to correlate the timing.

Distances were obtained by use of the quadrangle maps of the United States Geological Survey, which are of scale approximately 1 inch to the mile.

Results

Travel-time--The location of blasts and recording stations are indicated by the numbers 1 to 8 in Figure 1. This map is taken from a portion of the geologic map published by the Pennsylvania Department of Internal Affiars. It is seen that all of the observations except one are taken in or near the Leesport Cement-Rock. Tracings of some of the seismograms are shown in Figure 2. Each record is identified by two numbers, the first indicating the location of the blast, the second that of the recording station. The amount of explosive used is also indicated. Various phases are marked upon the records and those which have been attributed to the same type of wave are indicated by the same symbol. The travel-time for each phase is plotted as a function of the distance in Figure 3.

The waves indicated by phase A, which are undoubtedly longitudinal waves, are seen to travel with a velocity of 21,000 ft/sec. Since for most shots the path along which the waves travel lies entirely in the limestone-region, this velocity is attributed to longitudinal waves in limestone. Phase C represents waves having a velocity of 10,700 ft/sec. It seems fairly likely that these are transverse waves in limestone. Phase B represents a wave having a velocity of 18,000 ft/sec. It appears to be a well-defined wave but its nature remains in doubt. Two other phases, less definite, have been marked on some of the records. Their velocities are 14,800 and 12,500 ft/sec respectively. The occurrence of several phases which are not easily accounted for is in accord with the observations of Wood and Richter (Bull. Seis. Soc. Amer., v. 23, 95-110, 1933) in a similar study.

The travel-time curves for the principal phases observed here are straight lines through the origin. As is well known, this indicates that the depth of penetration of the corresponding waves is slight.

It is noteworthy that the travel-time of the longitudinal wave which traversed the Martinsburg Shale Area, lies on the curve determined by the other observations. It is known from geological evidence that the limestone dips beneath the shale and its depth in the vicinity of Station 7 has been estimated at 3,000 to 10,000 feet. Therefore, it is concluded that the velocity of longitudinal waves in the shale differs but little from that in the limestone. The later phases are not as distinct on this seismogram as on the others.

Factors affecting amplitude--Early in the investigation it became apparent that the motion was not transmitted equally well in all directions from the quarry. Relatively little energy was transmitted across the quarry so it was necessary to choose the recording location so that the path of the waves did not cross the quarry. For shots 4-7 and 6-3 (see Fig. 2) the recording station was on the wrong side of the quarry. This observation upon amplitudes is in accord with the conclusion reached above that the waves recorded do not penetrate to very great depths.

In certain cases abnormally low amplitudes have been observed while in a few cases no motion at all was recorded. Dr. B. L. Miller of the Department of Geology of Lehigh University has suggested that this may be due to certain faults in the limestone. It is expected that the additional data now being gathered will lead to a definite conclusion on this interesting possibility.

Acknowledgment--Practically all of the cement and crushed-stone manufacturers in this region are generously cooperating in this investigation. The seismic instruments used were donated by the Geophysical Research Corporation.

Lehigh University,
Bethelem, Pennsylvania

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF METEOROLOGY

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BACKGROUND FOR FIRE-WEATHER WARNINGS

E. B. Calvert

Forest-fires are among the factors which cause great economic losses to this country. Every year they take a heavy toll and in some years losses therefrom run into hundreds of millions of dollars, in addition to many lives. Practically all of the states having any considerable amount of timbered land, which is in the form of woodlots or forests, have state foresters under whom there are organizations for protection of forests from fires. The Government also has its Forest Service for guarding and protecting its immense forest reserves.

One of the activities of the Weather Bureau of which, perhaps, little is known to the general public, is its fire-weather warning service. Its purpose is to aid the forest-protection agencies--government, state, and private--by providing them with special weather-forecasts daily during the seasons of fire-hazard, especially warnings of the coming of conditions which favor the inception and spread of forest-fires. When such warnings are received, the protecting agencies take precautions by deploying men and equipment to points of vantage in the threatened areas. When unusually menacing conditions are forecast, logging operations are suspended, mills are shut down, and the crews are held in readiness to join the fire-fighting forces.

The fire-weather service of the Weather Bureau is organized into seven districts with headquarters as follows: 1, California, San Francisco; 2, Oregon, Portland; 3, Washington, Seattle; 4-5, Idaho and Montana (combined), Spokane; 6, Minnesota, Wisconsin, and Michigan, Chicago; 7, New England States, and Adirondacks, Boston; and 8, Southern Appalachian Region, Asheville.

Special meteorological stations, equipped with standard instruments, are located in the forested areas of these districts, the observers for the most part being employees of the fire-protecting agencies. The total number of these stations in all of the districts is approximately 550, distributed as follows: District No. 1, 140; District No. 2, 133; District No. 3, 135; District No. 4-5, 62; District No. 6, 40; District No. 7, 27; District No. 8, 13. During the season of fire-hazard, usually June to October, in the far western states and varying periods during March to October in the eastern states, observations taken at the special stations are telephoned or telegraphed daily to the district headquarters where the forecasters are located. Each district is divided for forecasting purposes into unit areas with climatic and topographic comparability, 10 to 15 in some districts. Separate forecasts and warnings are issued for these unit areas.

Forecasts and warnings are predicated on the general weather-map of the United States and Canada and on the reports from the stations in the forest, but the forecasters have been handicapped because, due to lack of personnel, it has not been possible to compute and compile the records made at the special stations and to establish normals for study purposes and for comparison with current conditions at the time forecasts and warnings are being prepared. Opportunity to compile these data presented itself through the Civil Works Administration. Persons were employed for the purpose at all the district headquarters, except Asheville (records in that district being for too short a period). In all, 56 persons were engaged in the work for a period of about 17 weeks.

Although the compilations varied somewhat in the different districts, the following statement applying to the California district is closely typical of all:

Means of the following were computed by months and by 10-day periods: Temperature, dew-point, relative humidity, vapor-pressure, at 8:00 a.m., 3:00 p.m., 5:00 p.m., local time; maximum and minimum temperatures; daily minimum relative humidity; precipitation; number of Class A, B, and C fires in National Forests; and number of lightning-fires in National Forests.

The number of days each month and the number of successive hours that the relative humidity was below a certain critical figure were computed for those stations equipped with hygro-thermographs.

Some idea of the amount of work involved in the California District alone (No. 1), which has 140 stations, can be gained from the fact that more than 250,000 computations of dew-point and more than 500,000 entries of humidity were required and a corresponding volume for other districts.

Concerning the purposes to which the data as compiled by the Civil Works Administration workers will be applied: Their application to the fire-weather forecasting problem is obvious, and their value in this connection will be many times the cost of compilation. They also will be used for other important purposes, some of which will be epitomized:

Minimum-humidity data will be used by forest experiment stations in rating forest-fire hazard for timber insurance.

Relative-humidity data are valuable for climatological purposes and in supplying demands relating to heating and ventilating, evaporation associated with hydro-electric and irrigation projects, entomology, silviculture, fire-control, fuel-moisture, soil-investigations, engineering, etc.

Data of temperature, relative humidity, and wind will supply needs for such information, in conjunction with data from other stations. Many of the fire-weather substations are located in areas from which such data are otherwise not available.

Most of the data will be made available to forestry supervisors, rangers, lookouts, and others directly concerned with fire prevention or control for day-to-day reference in determining conditions of hazard by comparison with current conditions.

All the data will be used for more close determinations of the relations between weather and fires, thereby placing all fire-phenomena on a much more definite physical and quantitative basis instead of the more or less empirical basis which obtains at present. This is of decided importance.

Forest-protection agents have long awaited compilations of the data now accomplished through the Civil Works Administration. It now will be practicable for them to make changes in protective methods and organizations based on definite knowledge instead of estimates and opinions, all tending to greater efficiency in guarding forestry resources.

Fundamental research in nursery practice, insect and blister-rust control, range and forestry management and influences, depend to a considerable extent on accurate and adequate weather-data. The whole compilation will be of inestimable value to those engaged in those lines of endeavor.

A fact of high importance is that the labor of the Civil Works Administration workers in compiling meteorological data is not of passing value. The value will grow with the years as other data accumulate and are combined with those already assembled.

U. S. Weather Bureau,
Washington, D. C.

REORGANIZATION OF OCEAN WEATHER-RECORDS FOR NEW APPLICATIONS

W. F. McDonald

The Weather Bureau archives of marine weather-records cover more than a century of ships' observations, mostly in original forms prepared by the observing officers. Some of Maury's extracts from ships' logs are among the three thousand volumes of weather log-books that comprise the body of earlier records. From the 1880's, a variety of list and ticket forms succeeded each other, but the character of the observations themselves has been remarkably homogeneous throughout the entire period of the accumulated records. This fact bespeaks the wisdom of the founders of systematic oceanic meteorology, notably Admiral Beaufort and Lieutenant Maury.

The variety of form and the physical volume of these accumulations of many decades have proved an embarrassment to the limited personnel and facilities of the Marine Division of the Weather Bureau, due to the manner in which the files have necessarily grown up on a basis of ocean-wide organization.

Ships have always submitted their weather-reports in the form of a "trip-record." The succession of observations, therefore, follows the course of the observing vessel, and the reports have been passed into general files according to the ocean concerned, the time-unit of the files being the month. To reach the matter relating to a given place or route has proved in these later years practically impossible due to the tremendous masses of material within each oceanic file in trip-reports that cross the oceans in a multitude of varying courses. To secure all the data available for a particular limited section of an ocean has involved working over the whole body of observations accumulated from that ocean.

While many ocean-weather averages and generalized digests have been compiled as the reports accumulated, the program of compilation has had its roots deep in the past, when modern problems of transoceanic aviation, transport of perishables, and other problems of modern commerce had not arisen. Modern needs call for a much more intensive exploration of the detail of our records for very practical purposes; the long-term averages comprise a valuable and essential body of data, but they constitute only the starting point for much work now demanded.

Although the ships observations were fairly comprehensive, usually including very valuable notations regarding the general state of the weather, as "overcast", "rain", "passing showers", "exceptional visibility", etc., in Beaufort's admirable short notations, and many records of clouds, wet-bulb temperatures, state of the sea, and other information, these data were in the main passed over in the older program of extraction of material. With the new value placed on such details (thanks to the fresh viewpoint of the Norwegian system of weather-analysis) and with the growing demands of transoceanic aviation upon us, there has been a pressing but hitherto unanswerable need to study these and other unused details of these ships' weather-observations.

The small regular staff of the Marine Division has been hopelessly swamped in any move to approach the huge problem of rehandling many tons of records to secure material bearing on new demands because our energies are almost wholly absorbed in the manifold details of supervising the present observing-program, fostering improvements in the standards and technique of ships' weather-observations, and handling the influx of reports that continue to arrive steadily day by day, for our digest and file.

Hence, when a part of the Federal Civil Works Administration fund was made available to the Weather Bureau, and the Marine Division was afforded an opportunity to partake in this unforeseen good fortune, we hastened to avail ourselves of the opportunity to plan work which would go at least part of the way towards reshaping these tremendous files of accumulated observations.

Three distinct avenues of approach were used. In New York City nearly a hundred Civil Works Administration employees have been engaged for four months in the project of reducing more than two million ships observations (covering the last twenty years) to the form of punch-card records for sorting and tabulation by machine. This method of handling is truly modern, and admits of the most satisfactory treatment of mass-statistics with a minimum of effort. The punching is planned to enable us (if desirable) to break down the files of observed data to unit areas as small as ocean-squares only one degree of latitude and longitude on the side. Sorting, classification, and tabulation can be mechanically performed at a rapid rate. The product of this unit has been two and a quarter million punch-card records, at a total cost of less than two cents per completed card.

One hundred and forty other workers were engaged elsewhere in the marine project, in four working units, at converting another three million ocean weather-observations to a form which can be manually sorted and filed; with this accomplished, we have access to the records by unit squares of reasonably limited size. These earlier records are of such heterogeneous character as not to lend themselves to use in a quickly organized and short-lived punch-card project such as the Civil Works Administration program necessarily involved.

The objectives, towards which these 241 people were directed in the marine phases of the Weather Bureau's Civil Works Administration project, have been very fully approximated, and the Marine Division will now, in the use of the accumulated records, be placed many years ahead of the position we held under our former, unaided, basis of operation. We shall be able at last to approach the task of sorting out some of the elements of a climatology of the North Atlantic Ocean and to a lesser degree, of the North Pacific and other oceans.

The massed records of ships' weather-observations will be reclassified and reorganized into files which will draw into clean-cut groups of observational material, all the available reports related to individual oceanic locations, or suitable ocean-squares of latitude and longitude.

Simple averages of weather-elements will for many areas be amplified into month-to-month histories. The sequence of weather-changes over the oceans can be partially investigated and recorded. We shall be able to begin some of those studies, so long needed, regarding the relations of oceanic and continental weather-conditions, possible sources of climatic fluctuations, weather abnormalities, etc.

It will be possible to check to some degree upon the results of such short-period weather-surveys as those recently undertaken along the Greenland-Iceland route to Europe. A limited weather-survey may or may not be representative of the long-term complexion of the weather-conditions over such a route. Enough is already known of fluctuations within the climatic sphere to speak a word of caution regarding the certitude with which the results of any relatively brief examination of a weather situation may be accepted.

Studies for selection of oceanic flying routes also raise other questions such as: Where are thunder-storm areas or bands most likely to be found? What is the hazard of sleet, low-cloud, or squall condition over the different portions of certain proposed ocean-routes? What do the records of past years show regarding the prevalence of more consistently favorable flying weather, such as high visibility for sighting "floating island" or other difficult mid-ocean landing-places, etc.?

The movement of perishable cargoes, or cargo subject to climatic damage, over long ocean-routes crossing in the same voyage tropical and temperate seas has also raised new questions regarding oceanic climates. Air-conditioning on shipboard is in process of development for passenger and cargo spaces of ships trading in the tropics, and marine data must be brought to bear upon this and other problems of modern marine transport.

Forecasting for any area now involves more than ever before a knowledge of the meteorology of the oceans. Averages must be broken down to time-histories, and the sequence of events over the continents requires correlation with concurrent sequences over the great water areas, especially at the "centers of action."

Thanks to the unexpected and marvelous opportunity which arose from the Civil Works Administration plan of employment, the Marine Division has been enabled to go far towards reorganization of a total of about five millions of ocean weather-observations so that the material for any specific area can be reached for study and use--information that may be brought to bear upon the many questions still open that require a more adequate knowledge of marine climatology and meteorology for their solution.

U. S. Weather Bureau,
Washington, D. C.

CLIMATOLOGICAL WORK ACCOMPLISHED THROUGH COOPERATION WITH THE UNITED STATES CIVIL WORKS ADMINISTRATION

J. B. Kincer

The climatological service of the Weather Bureau involves the maintenance of nearly 5,000 cooperative meteorological stations, the observers at which make daily observations of temperature, precipitation, and other phases of weather-conditions. Each observer prepares a monthly report in triplicate, one for retention locally and another for the section-center where state-wide data are summarized and published in monthly and annual reports; the third is furnished to the central office in Washington where, after proper checking, it becomes a part of the permanent climatic record of the Bureau. The value of a weather-record increases with its length, and, for the preparation of charts, it is highly desirable that all data refer to or cover identical periods of time. This is not the case with records on file, for the stations were established from time to time, as opportunity to secure competent observers was afforded and funds became available for providing equipments. Very few cooperative records go back more than half a century and most of them are less than 40 years in length. The greatest expansion of our climatological service occurred in the nineties and many records began during that decade.

At the time of compiling data for the publication of the climatological sections of the Atlas of American Agriculture, an examination of the rainfall-records indicated that a large number were complete for the 20 years from 1895 to 1914, but it was not considered advisable to go back of 1894 because of the rapid diminution in numbers for successive prior years. Therefore, the period 1895 to 1914 was adopted as the base-time, and all shorter records, those of ten years or more, were reduced to this period. About 1,600 stations had complete records and some 2,000 had to be reduced. The method of reduction is explained in a paper published in the Monthly Weather Review for May 1917 (pp. 233-235).

Since 1914, the latest date used in the Atlas charts, nearly 20 additional years of data have been added to the records, which greatly increases their value for climatological purposes. Through cooperation of the Civil Works Administration, an opportunity was afforded to compile precipitation-data for a much longer period than that represented by the Atlas charts, and this has been done. More than 200 clerical workers were employed and these were assigned to the several section-centers of the Bureau, ranging in number from four to seven for the different stations, depending on the mass of material to be compiled.

All precipitation-records--monthly, seasonal, and annual--have been reduced to a uniform 35-year period from 1898 to 1932, inclusive. The data thus compiled are now available for use as normals for the some 4,500 stations involved and for the revision of precipitation-maps as opportunity offers.

In addition to reducing data to the uniform 35-year period, other phases of precipitation-records have been summarized, such as the wettest and driest periods of record, by years, seasons, and months, the heaviest and lightest seasonal snowfall, and other important climatic features.

There has been prepared also a complete set of substation index-cards, containing in detail the history of each cooperative station. These include location of the station, elevation, instrumental equipment, and nature of exposure. Also the names and periods of service of all observers that have had charge of the stations, together with changes in station-locations. On the reverse sides of the cards have been entered a summary of all records made at the station from the beginning of observations up to the end of 1932. The data summarized include the averages of monthly and annual temperatures, the average maximum and minimum, and the highest and lowest of record for each month and for the year. Also the average monthly precipitation, and the greatest and least monthly and annual amounts, the greatest 24-hour falls, and the average monthly and seasonal snowfall. This affords a complete history of all cooperative stations of the Bureau from their establishment up to the present time.

At the central office in Washington, seven employees have compiled data on diurnal variations in atmospheric pressure for one year for 50 Weather Bureau stations scattered throughout the United States. The data are for use in studies and investigations as to the effect of pressure-variations on the incident of sickness from various causes in different parts of the country. The project relates to the question of Public Health Investigations. They have also compiled many records for the study of long-range forecasting, including the tabulation of daily temperature-data for six stations in the United States and two in Europe, for the 50-year period from 1878 to 1927. A large number of monthly temperature-data for nearly 5,000 cooperative stations of the Weather Bureau have been tabulated in manuscript form as permanent climatic records.

The cooperation of the Civil Works Administration has been of great value to the climatological service of the Bureau, enabling it to make these much-needed compilations of data that otherwise would have been impossible.

U. S. Weather Bureau,
Washington, D. C.

THE PURPOSE OF THE COMPILATIONS OF AEROLOGICAL DATA BEING MADE UNDER THE CIVIL WORKS ADMINISTRATION PROGRAM OF THE WEATHER BUREAU

Louis P. Harrison

Beginning about the middle of December, 1933, seven Civil Works Administration sub-projects involving the compilation of aerological data were set into operation at 24 stations scattered over the United States, a total of about 169 persons thus being employed. The work on which these people were engaged, extending over a period of time ranging from two to four and one-half months, falls naturally into three general categories which will be discussed in turn.

I--Compilation of Polar-Year data

The first general category consisted in the compilation of data for the Polar Year, which ran from August, 1932, to August, 1933, inclusive. Under this head, two sub-projects were carried out.

(1) Tabulation of hourly values of various meteorological elements for 29 Réseau Mondial stations in the United States--This work required the reading of autographic records of wind-velocity and wind-direction, barometric pressure, temperature, etc., for every hour of the Polar Year for 29 selected stations and the tabulation and summarization of the results thus obtained in the form of monthly and annual tables. Some of the selected stations were located in Alaska near the source whence many of the outbursts of polar air occurring so frequently here in winter are derived. Ammunition is thus provided to assist in a world-wide attack upon some of the most pressing problems confronting meteorologists today, namely, the elucidation of the causes initiating and conducing to the development, growth, and decay of cyclones and anticyclones, particularly from the viewpoint of the so-called Polar-Front Theory which has been brought to the forefront of meteorological thought in recent times, largely through the efforts of the Norwegian school.

(2) Tabulation of upper-air wind-data secured by means of pilot-balloon observations during the Polar Year--In this case, graphs showing the variation of wind-velocity and wind-direction with height in the free air were read off to give the wind at certain standard levels. Data were thus obtained for eight selected days of each month of the Polar Year from a total of 80 pilot-balloon stations in the United States, 76 of these under the Weather Bureau and four under the Navy Department. This material is invaluable for the study of the structure of cyclones and anticyclones as regards movements of the air-masses which go to make them up. When analyzed in conjunction with surface-data such as that previously mentioned and with free-air data obtained by means of aeroplanes and sounding balloons on a world-wide scale, these data should go a long way toward disclosing the mechanisms of the highs and lows which control our weather.

II--Graphical representation and tabulation of data showing diurnal variation of various meteorological elements in the free air

The second general category of work was based on data derived from a number of series of kite-observations made over a period of from 7 to 10 years at six aerological stations in the United States. The values of barometric pressure, relative humidity, vapor-pressure, and wind-velocity (also wind-direction) for various fixed levels in the free air were plotted against time and smooth curves were drawn from which were read the values of the elements at each of the 24 hours of the day. The tabulation of these results provides material necessary for the study of the diurnal variation in the free air of the elements in question. A study of such material is of value in that we are thus led to a betterment or extension of our knowledge of the periodic physical processes occurring in the atmosphere and are enabled to distinguish more clearly what are aperiodic, and what periodic changes.

III--Statistical compilation of various meteorological data for the aid of aerial navigation and for studies of the general circulation of the atmosphere

The third general category included four sub-projects, each bearing an important relationship to aerial navigation.

(1) Compilation of airways meteorological data for stations along and adjacent to established airways--Airways meteorological data obtained largely from observations made hourly over a period of two years at 177 stations in the United States were summarized and statistically analyzed. The character of the data in question may be seen from the five sub-divisions into which they were broken down: (a) General conditions, including such items as fog, ground fog, haze, smoke, dust, rain, snow, sleet, hail, freezing rain, sprinkling, mist, and thunder-storms with a symbolic representation of the intensity where necessary; (b) ceiling height; (c) visibility; (d) wind-direction and wind-velocity; and (e) temperature and dew-point. The purpose of such analyses of meteorological data is to furnish the material for a study of climate from the viewpoint of the aviator. From such information air-transport companies can learn what places to avoid and what airways can be operated most safely, while governmental agencies can learn what regions require special air navigational aids, etc.

(2) Statistical analysis of upper-air winds to give the frequency of winds between certain velocity-limits for the various directions--Following the recommendations of the International Commission for the Exploration of the Upper Air, records of 57 pilot-balloon stations for the period January, 1925, to July, 1932, inclusive, were analyzed in respect to frequencies of winds between 0 and 1, 2 and 7, 8 and 14, 15 and 21, and greater than 21 meters per second for the 16 points of the compass for certain fixed levels in the free air. This information is of value in the preparation of flying schedules along points for which the data in question are available, in the evaluation of various sites as possible lighter-than-airship bases, etc.

(3) Computation of wind-roses and resultant winds for selected pilot-balloon stations in the central and western portions of the United States--Pilot-balloon data obtained from 33 stations located in central and western United States and having three or more years of record were employed as a basis for the computation of monthly wind-roses and resultant winds for certain fixed levels in the free air. These results are of great value in the establishment of flying schedules and in the study of the general circulation of the atmosphere. This work when completed will provide, in conjunction with similar work already published for the eastern portion of the United States, an upper-air wind-survey of the entire United States extending to a height of four kilometers above sea-level.

(4) Compilation of upper-air wind-data by months for oceanic areas subdivided into 5° squares of latitude and longitude--All the available published pilot-balloon and some kite data for the oceans, largely from German sources, plus numerous unpublished pilot-balloon observational data obtained by United States Naval vessels were compiled according to the month and to the 5° squares of latitude and longitude in which the respective observations were taken. The directions were given to 16 points of the compass, while the levels used were: Surface, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0, etc., km above sea-level. It is planned to compute wind-roses, resultant winds, and frequencies of certain velocity-categories for each direction from these data. In addition, we have asked the cooperation of a number of countries bordering on the Atlantic Ocean to provide similar data by seasons for a distribution of stations along their Atlantic coasts and adjacent islands. These results are of urgent necessity for the planning of regular flying schedules across the Atlantic Ocean which we anticipate are just over the horizon. Moreover, from a purely meteorological viewpoint, these data should be of inestimable value for the investigation of the general circulation of the atmosphere over the oceans about which our knowledge is as yet quite incomplete.

U. S. Weather Bureau, Washington, D. C.

ADJUSTMENT AND STANDARDIZATION OF THE WEATHER BUREAU'S RIVER-GAGE SYSTEM WITH PUBLIC WORKS FUNDS

M. W. Hayes

River-stage forecasting was undertaken by the Signal Service, which was the predecessor of the present Weather Bureau, in 1872, and its beginning may be said to be almost coincident with the organization of the weather-service. At the start, as might be expected, the work was rough. The entire service was new, and while it was filled with enthusiastic men they were without experience. In fact, there were no men at that time who were experienced in predicting river-stages, and several years of experimentation were necessary before the efforts of the forecasters were accepted as something of real and practical value.

There is little to indicate the exact degree of accuracy attained in the early efforts of river-stage forecasting, but demands for the expansion of the service, particularly in regions subject to disastrous overflows, convince us that it must have been encouraging.

Growth has been gradual in the slightly more than 60 years the service has been in existence, and on June 30, 1933, there were in operation 64 forecasting centers and 705 river-gage stations. The number of the latter has been reduced to 661 since last June on account of the lack of funds, but it is hoped most of the suspended stations will again be in operation before the recurrence of a flood-year similar to 1927.

The Weather Bureau has never had the funds to erect at one time more than a few river-gages of substantial and standardized types, and every major flood has washed out a comparatively large number of the structures in use. Replacements in most instances have necessarily been of an unsatisfactory type.

To overcome these undesirable conditions the Federal Emergency Administration of Public Works was asked to allot the sum of $150,000 for the rehabilitation of Weather Bureau river-gages. The request was granted in September, 1933, and the Bureau is now engaged on its own account and in cooperation with other governmental agencies in a campaign to place on a standardized and substantial basis all the gages used in stage- and flood-forecasting.

The program provides for (1) distance stage-recorders at about 15 district centers, where public interests demand almost continuous information of river-stages in important rises and floods, (2) ordinary stage-recorders at about 50 strategic points at which quantitative flow-measurements will be made by the United States Geological Survey, and (3) eye-reading gages at approximately 596 stations. Of this number about 200 will be wire-weight gages attached to bridge-rails, and 396 will be staff- or slope-gages.

These gages are not all the property of the Weather Bureau; about 250 of them are owned and maintained by the Engineer Corps of the Army, and the Geological Survey, but through a plan of close cooperation between these services and the Weather Bureau there will be available for river-forecast work at the close of the present year a network of 661 gages of the types best suited for the respective locations, and in good, substantial condition and thorough adjustment.

The accuracy and timeliness of the river-forecasts of the Bureau have, for a long time, been considered quite satisfactory by the general public, but the officials of the Bureau have always realized that the system under which they are made has an inherent disadvantage, inasmuch as it has never been expressed in standardized formulas. Each forecaster has a set of rules for the rivers in his district, but these rules must be applied in individual cases through the experience of the forecaster. It is impossible for a forecaster to put a large part of his knowledge on paper, and when he is no longer available for this work his successor must begin immediately to make an intensive study of the regimen of the rivers in his district and the effect on the rivers of rains of varying intensity and varying distribution. He must also become familiar with the relation of runoff to precipitation as it may be affected by the season of the year, the condition of the soil, and numerous other things that must be given consideration. Even an intensive study does not thoroughly qualify a forecaster, but actual experience must be had before he feels sure of himself.

Discharge-observations or rating curves have been used to a very minor extent in Weather Bureau work. It has not been possible to employ them in any large way because they were not available. However, since 1922, and particularly since 1927, much stress has been placed on flood-protection, and in the last few years inland navigation and power-development have progressed steadily. Due to these facts information in regard to the quantitative flow of streams is increasing more rapidly than ever before.

The Weather Bureau makes no stream-flow measurements, but through the cooperation of the Geological Survey rating-curves will be available for strategic points on the important rivers of the country, and the officials of the Bureau will begin a study of the application of rating-curves to river-stage and flood-forecasting. It is hoped and thought that this study will remove a reasonable amount of the personal element that now surrounds forecasting, and will make it possible to refine forecasts somewhat more than at present, especially on the large rivers, and will enable a forecaster to leave for his successor formulas that are based on sound and well-understood principles.

While officials of the Bureau are viewing the use of rating-curves with hope and conservative enthusiasm, they realize fully that these curves can be no more than an important aid, that current meteorological information will always be indispensable in river forecasting, and that if, in rehabilitating and standardizing the network of river-gage stations, the meteorological stations are neglected no satisfactory measure of success can be attained.

U. S. Weather Bureau,
Washington, D. C.

REPORT ON SOUNDING-BALLOON WORK CARRIED OUT IN THE UNITED STATES DURING THE POLAR YEAR

J. C. Ballard

Sounding-balloon observations were made in the United States during the Polar Year at Dallas, Texas; Omaha, Nebraska, and Ellendale and Pembina, North Dakota. These stations lie approximately on a north-south line and they extend from 31° to 49° north latitude. Altogether, 234 meteorographs were released. Eighty-five per cent of them have been found and returned. The observations were made in series consisting of three flights each covering approximately 18 hours. Two such series were made at each station per month, the flights being made on the days and at the times designated by the International Commission.

All of the records returned from the Polar Year series have been computed and tabulated as prescribed by the International Commission for the Exploration of the Upper Air. This plan includes tabulation of the temperature, pressure, and relative humidity at all the significant levels, at the standard isobaric levels, at the standard geometric levels, and at the standard geodynamic levels. Whenever possible the balloons were watched with one or with two theodolites and the wind-velocities and wind-directions were computed. The wind-data, also, were tabulated for the standard geodynamic levels. All of these data were entered on special forms devised by the Commission, a single observation on each page, so that the copies would be ready to go directly to the printer. These forms were mailed last February to the International Commission which is to supervise the publication of all upper-air data obtained during the Polar Year.

The greatest height reached in this series of flights was about 26 km, but the number of balloons reaching heights greater than 22 km was relatively small. However, the maximum heights reached were much more uniform than in previous series so that the average height reached, about 17.5 km, was higher by nearly 2 km than that reached in any other long series in this country.

This greater uniformity in heights reached indicates, among other things, that the balloons used were of a more uniform quality than those previously obtained. Another factor which helped considerably to make these records longer was that there was a comparatively small number of failures in record at low altitudes caused by stopping of the clock. The clocks used in this series were all washed thoroughly in carbon tetrachloride the day before using and oiled with a very small amount of a special low-temperature oil. The effect of this treatment of the clocks was obviously very beneficial.

The distribution of the observations in this series with respect to time and place was considerably different from that in many previous series in which observations were made daily throughout a calendar month at a single station. Both types of distribution of observations furnish data best suited for particular types of study. The schedule followed during the Polar Year provided data for the study of a number of features which heretofore have been untouched. Some of the more important of these are as follows:

(1) Three observations were made at each station with only a relatively short lapse of time between flights. This provides data at shorter intervals for study purposes and also affords, to a certain extent, a check on the instrumental records.

(2) The observations furnish, in several cases, simultaneous data up to and in the stratosphere for different parts of a high- or low-pressure area. Studies of these individual cases should yield valuable information.

(3) Data were furnished which made it possible to determine the annual variation of pressure at altitudes up to 15 km and the annual variation of the height of the tropopause at each of the stations. The annual pressure-variation at altitudes up to 4 km had already been determined for a number of stations from kite records but the information for greater heights is especially interesting from a number of standpoints and may prove to be of considerable value in studies of the changing seasonal characteristics of the pressure-areas.

(4) The latitudinal variation of pressure aloft and the latitudinal variation of the height of the tropopause in the various months can be studied from these data. This ties in with the point just mentioned and both of them taken together should assist materially in reaching a better understanding of the movements and characteristics of storms.

(5) Data were furnished, for the first time, which made it possible to determine with some degree of accuracy the magnitude of the effect of solar insolation on the record of temperature made by the meteorograph. It had previously been assumed that this effect was present to some extent but the magnitude of the effect was entirely unknown.

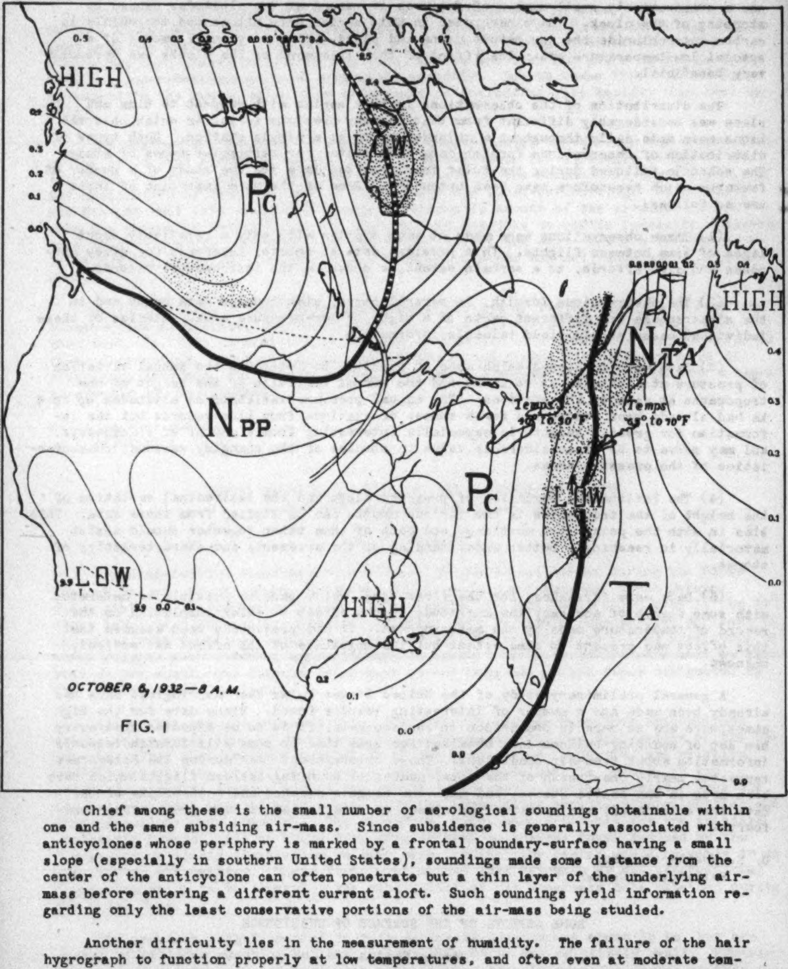
A general preliminary study of the United States Polar Year aerological data has already been made and a number of interesting results found. Since data for the high atmosphere are so rare in comparison to surface-data, it is to be expected that every new set of sounding-balloon data obtained for some time to come will furnish valuable information about free-air conditions. Those observations made during the Polar Year represent nearly one-fourth of the total number of sounding-balloon flights which have been made in the United States, and when the heights reached and reliability of the data are considered, the relative importance of this series is even greater than one-fourth.

U. S. Weather Bureau,
Washington, D. C.

SOME ASPECTS OF THE SURFACE OF SUBSIDENCE

Jerome Namias

The problem of subsidence within the atmosphere has received comparatively little attention in synoptic studies embodying aerological material. Only the most general statements are usually made in regard to this little-understood though important process always occurring within selected portions of the atmosphere. Several difficulties immediately associate themselves with a rigorous treatment of the phenomenon as observed.



OCTOBER 6, 1932—8 A.M.

FIG. 1

Chief among these is the small number of aerological soundings obtainable within one and the same subsiding air-mass. Since subsidence is generally associated with anticyclones whose periphery is marked by a frontal boundary-surface having a small slope (especially in southern United States), soundings made some distance from the center of the anticyclone can often penetrate but a thin layer of the underlying air-mass before entering a different current aloft. Such soundings yield information regarding only the least conservative portions of the air-mass being studied.

Another difficulty lies in the measurement of humidity. The failure of the hair hygrograph to function properly at low temperatures, and often even at moderate temperatures, makes the recorded values of relative humidity confusing. Consequently the computed values of specific humidity and equivalent potential-temperature are not sufficiently accurate for quantitative comparisons, although the general trends and approximate values are of considerable value in identifying the inversions. The measurement of temperature and pressure enables us to get reliable values of potential temperature which are important in the study of subsidence.

UPPER-AIR CONDITIONS — OCTOBER 4-9, 1932

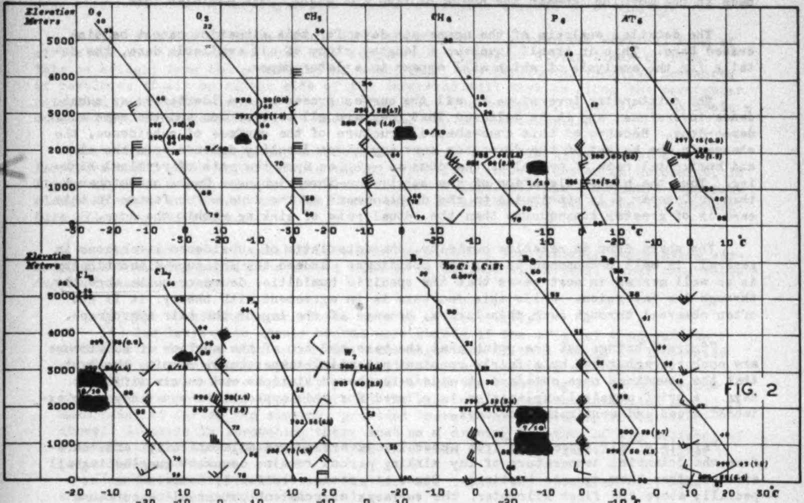


FIG. 2

This paper is a brief report showing a few points of interest in connection with a well-defined surface of subsidence. Several similar cross-sections are being studied minutely with the hope of finally being able to arrive at general conclusions.

The situation chosen for illustration is that of October 4 to 9, 1932. An exceptionally slow-moving and well-defined front marked the boundary between a transitional Polar Continental air-mass and a Tropical Maritime current to the east. The characteristic air-mass and frontal features of the period are well typified by the analyzed morning map for October 6, 1932, the main features of which are reproduced in Figure 1. From the pressure distribution it is evident that the Pc-Tg front has a slow rate of movement. This is a case in which we have a front which becomes sharper and sharper because of the continued southward flow of cold air on the western side and northward flow of warm air on the eastern side of the discontinuity.

The comparative stagnation of the system is helpful in this study of the subsidence occurring behind the front, since the slow rate of travel permits aerological sounds to be obtained on several mornings within the Pc air-mass. Since there is such a large wind-vector difference at the front, the slope must be steep. This aids in securing representative data of a good thickness of Pc air behind the front.

In Figure 2 are shown temperature-altitude curves at various stations during the October 4 to 9, 1932, period. The numbers to the right of the curves are relative humidities at significant points. Those to the left are the potential temperatures, in degrees absolute. The numbers in parentheses are the specific humidities, in grams per kilogram. Pilot-balloon wind-observations for different elevations are shown by arrows; the direction expressed with north to the top of the chart, and the velocities on the Beaufort scale by the number of half barbs. For example, in a north wind the barbs representing velocity are at the top and the shaft points straight downward; in an east wind the barbs are at the right and the shaft extends horizontally to the left. Cloud-forms and amounts are also shown. The station names are abbreviated at the top of the curves as follows: O, Omaha, Nebraska; CH, Chicago, Illinois; P, Pensacola, Florida; AT, Atlanta, Georgia; CL, Cleveland, Ohio; W, Washington, D. C.; B, Boston, Massachusetts. The subscript refers to the date of the sounding. All flights were made in the morning between the hours of five and eight, 75th meridian time.

The detailed analysis of the upper-air data for this situation cannot be discussed here. This in itself involves a lengthy study of all available data, the details for the analysis of which will appear in a later paper.

The outstanding inversions in all the curves presented are identified as subsidence-inversions, and it is believed that they are all part of one and the same subsidence-dome. Because of this dome-shaped structure of the surface of subsidence, the change in the height of the inversion over any given locality depends upon the slope and horizontal rate of travel of the dome as well as upon the rate of vertical sinking. Thus the higher elevation of the subsidence-inversion over Omaha on October 5 than on October 4 is attributed to the displacement of the dome, which factor in this case is of greater consequence than the actual rate of sinking within the dome.

The sharp drop in relative humidity, characteristic of subsidence-inversions in general, is well pronounced in all the soundings. Indeed the moisture-discontinuity is so well marked in most cases that the specific humidities decrease quite abruptly through the inversion. While this decrease is in agreement with theory, it is not often observed through such thin layers, because of the lag of the hair hygrograph.

Figure 2 brings out the point that the base and top of the surface of subsidence are each characterized by a fairly constant potential-temperature, despite the fact that the soundings were obtained at widely-scattered stations and on six different days. A brief physical explanation is offered for this approximate constancy over extended areas and continuing for days.

Parcels of air descending from upper levels are warmed adiabatically, and therefore the potential temperature of any sinking parcel remains constant (neglecting all effects other than dynamic heating). Since air-masses are fairly homogeneous, especially above the first kilometer, the surfaces of constant potential-temperature within the air-mass will be nearly horizontal before subsidence begins. Evenly distributed sinking of an individual layer of such an air-mass will lead to a downward displacement of the surfaces of constant potential-temperature bounding the subsiding layer.

For example, let us assume that a horizontal inversion has been established at upper levels through radiation from the upper surface of a haze and moisture discontinuity, as suggested by Mal [see reference 1], and that the potential temperatures at the base and top of this inversion are θ_1 and θ_2 respectively. With a sinking of this inversion these two surfaces, θ_1 and θ_2, will still characterize the base and top of the inversion, although they will be pressed closer together. It is to be noted that we are here assuming that the mass of air within a unit column extending from the base to the top of the inversion remains constant. In other words, no horizontal stretching is occurring.

Obviously, divergence must accompany subsidence--whether or not it is the result or cause of it. One common example of divergence of flow is that which takes place entirely from the lower layers in an anticyclone because of the frictional outflow across the surface-isobars. This type of subsidence probably is of most consequence in the semi-permanent highs, where there are long periods of stagnation. In this event, the surfaces θ_1 and θ_2 continue to represent the subsidence-inversion.

But the fact that subsidence-inversions are invariably found to slope, and often are identified as dome-shaped surfaces, seems to indicate that the divergence is unequally distributed. Thus the fact that the tops of subsidence-domes are frequently found over stagnating anticyclonic centers is probably due to small outflow from the central portion, as is suggested by the light winds.

If the divergence has its maximum at some upper level, say above the inversion, the stretching of layers will result in a drawing together of the isopotential temperature-surfaces. This may occur to such an extent that θ_2 no longer represents the inversion-top but some potential temperature greater than θ_2.

The net effect of varying divergence, both in the vertical and horizontal fields, is, then, to warp the surfaces of constant potential-temperature. In our illustrative case this would mean a warping of our inversion-surface bounded by θ_1 and θ_2.

A discontinuity of lapse-rate within the atmosphere guides the vertical flow of air, since the isotherms of potential temperature represent stream-lines of flow. This is evident from the principles of stability. Any horizontal relative movements of particles of air on either side of the inversion will thus be along the particular potential isothermal surfaces on which they lie. The tendency, then, is to maintain a constant potential-temperature at the base and top of the inversion.

Quite often, in stagnating anticyclones, there is little air-movement at the inversion-base, while rapid flow is taking place just above. Boston on October 8, in Figure 2, shows a good example of this. In such a case, air has a downward component along the upper surface of the dome, each particle maintaining its potential temperature all along its route.

In the ideal case of subsidence occurring within a horizontally homogeneous air-mass, the following conditions should hold if we neglect all effects other than those due to dynamic sinking:

(1) The subsiding layer should warm up adiabatically.

(2) The lapse-rate should become more stable if the original temperature-distribution is less than adiabatic. The magnitude of this change in lapse-rate should be in accord with well-known subsidence-formulae [see reference 2].

(3) An inversion originally present within the subsiding air should become sharper. The potential temperature at the base and top of the inversion should remain constant during the sinking, provided there is no stretching of the layer above. If there is stretching there must be a drawing together of the surfaces of constant potential-temperature and the inversion will reach surfaces of higher potential-temperatures.

(4) The specific humidity at the base and top of the inversion will remain constant in the event of no stretching.

Such a simple behavior of elements is probably never observed within the atmosphere. Other effects complicate the problem, chief among which are radiation, turbulent exchange, and the mechanical effect of frontal movements.

Here an attempt is made to explain, by means of these disturbing factors, some of the observed deviations from the four conditions and to offer a few suggestions for the determination of the relative magnitudes of these influences.

Figure 3 shows the potential temperatures observed at the top and base of the principal subsidence-inversion of October 4 to 9, 1932, at the different places on the several days as shown in Figure 2. In the left half of the diagram are shown the potential temperatures of the lower boundary of the inversion at whatever altitudes they were observed, that is, θ_1 (potential temperature) against Z_1 (altitude). In the right half of the diagram are plotted the potential temperatures at the upper boundary of the surface of subsidence, that is, θ_2 against Z_2. The station-abbreviations and the date of the sounding (subscript) are given beside each point. The range in either case is not greater than 7°, which would indicate that other factors are secondary to subsidence. θ_2 seems to remain nearly constant up to two kilometers, and then to vary in a seemingly orderly fashion. This apparent regular variation in θ_2 with elevation may be peculiar to this case, and might even be accidental. No obvious explanation presents itself. However, if the potential-temperature minimum in the curve is actually a time-minimum (since Omaha on October 4 is the earliest sounding), it may be that continued sinking and spreading air over the surface of subsidence may bring down potentially warmer air, and thus help to explain the increase, shown by later soundings.

The relative constancy of θ_2 below two kilometers indicates the absence of further spreading of air on top of the dome. From the data it seems that above two kilometers θ_1 remains more constant than θ_2, which may mean that above this level radiation-effects are less important than spreading. On the other hand, below two kilometers the relative constancy of θ_2 indicates that radiation is the dominating factor in producing such variations in θ_1 at corresponding levels.

FIG. 3

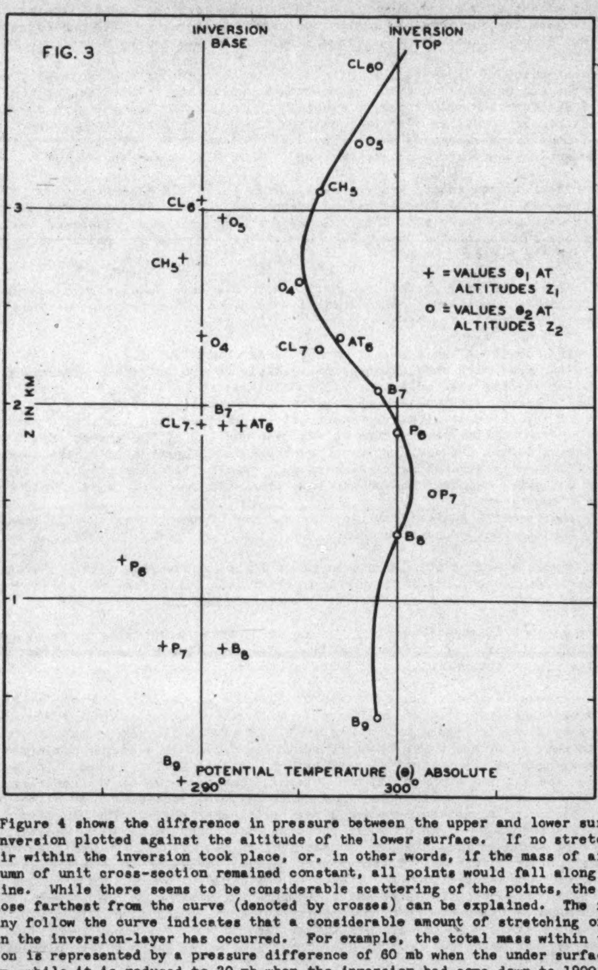


Figure 4 shows the difference in pressure between the upper and lower surfaces of the inversion plotted against the altitude of the lower surface. If no stretching of the air within the inversion took place, or, in other words, if the mass of air within a column of unit cross-section remained constant, all points would fall along a vertical line. While there seems to be considerable scattering of the points, the position of those farthest from the curve (denoted by crosses) can be explained. The fact that so many follow the curve indicates that a considerable amount of stretching of the air within the inversion-layer has occurred. For example, the total mass within the inversion is represented by a pressure difference of 60 mb when the under surface was at 3100 m, while it is reduced to 20 mb when the inversion had come down to 1900 m, or one-third of its former mass. This must be accounted for in terms of horizontal divergence of air-flow, with the consequent reduction of mass within a vertical column.

In regard to points lying appreciably off the curve, Atlanta on October 6 has a double inversion (see Fig. 2). Whether the upper inversion is a newly formed one, whether it is a part of the original, or whether it is due to waves on the inversion-

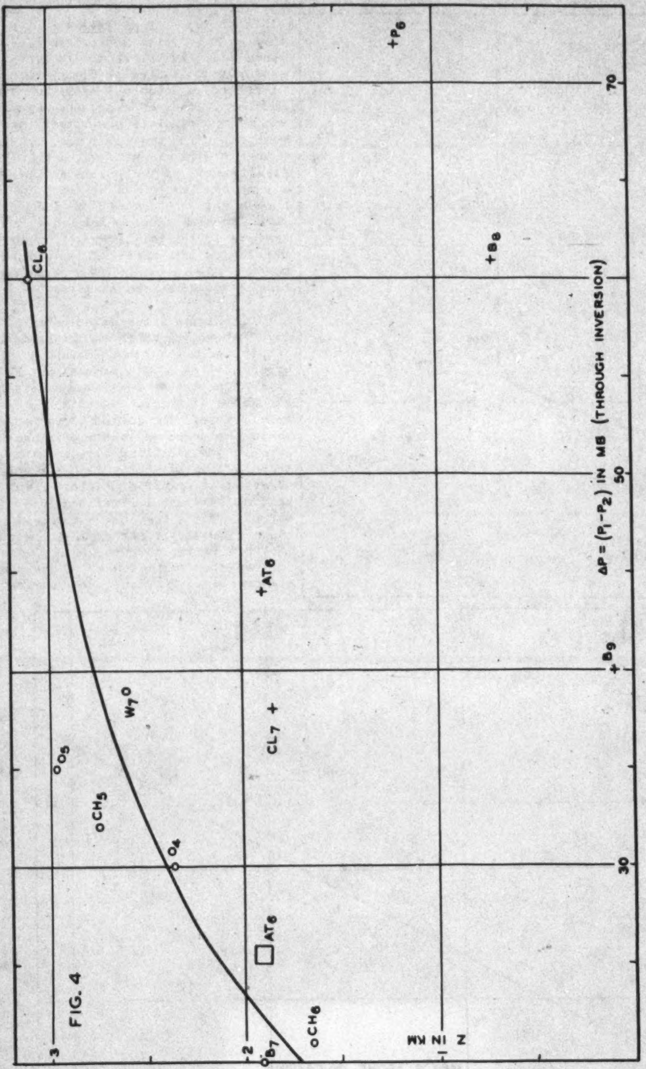

Z IN KM
1
2
3
30
50
70
ΔP = (P₁-P₂) IN MB (THROUGH INVERSION)
CL6
O5
CH5
W7
O4
AT6
AT6
CL7
B7
CH6
B9
B8
P6

FIG. 4

surface [see reference 3] it is impossible to say. If we take the first inversion as being the original, Atlanta will fall close to the curve, as shown by the square in Figure 4. Cleveland on October 7 seems to have another surface of subsidence above the main one. This undoubtedly has some effect on the lower one, but the nature of this is not yet clear. The disagreement in the points at low levels is best explained as being due to a combination of radiation- and turbulence-effects, which are at a maximum in the low layers. The complexity of this phase of the problem makes a discussion of it more suited to a later more general paper.

In Figure 5 the lapse-rate in the layer above the surface of subsidence is plotted against the elevation of the upper surface of the inversion. As the inversion becomes lower the subsiding air above it should become more and more stable. The dotted curve represents the computed values of lapse-rate in the subsiding air, assuming that it started at the high elevation observed at Omaha on October 5, and that no horizontal stretching occurred. Since the observed values of lapse-rate show a far more stable condition than the computed values, it follows that a great deal of horizontal divergence of flow must have occurred.

FIG. 5

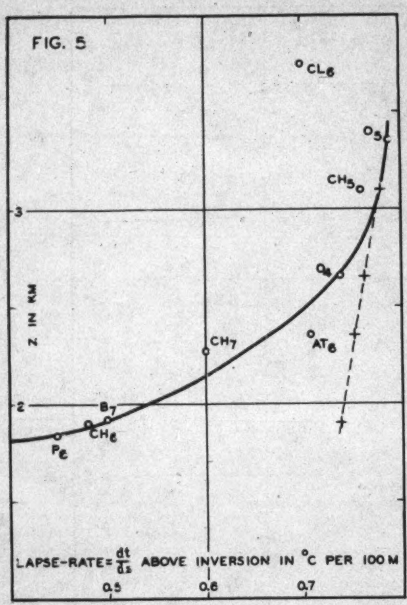
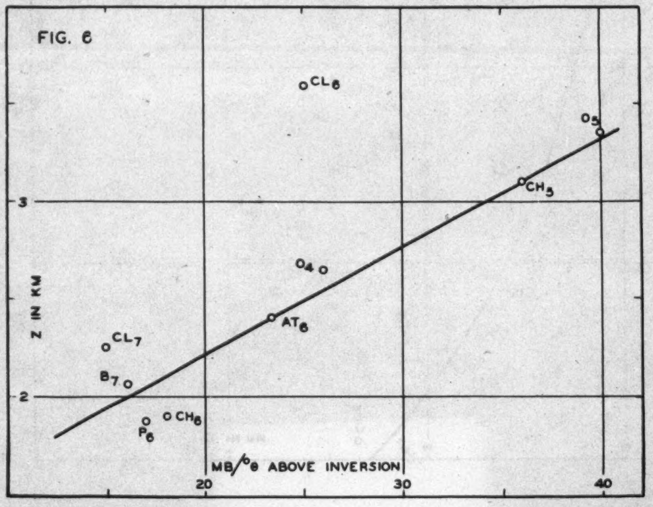


FIG. 6



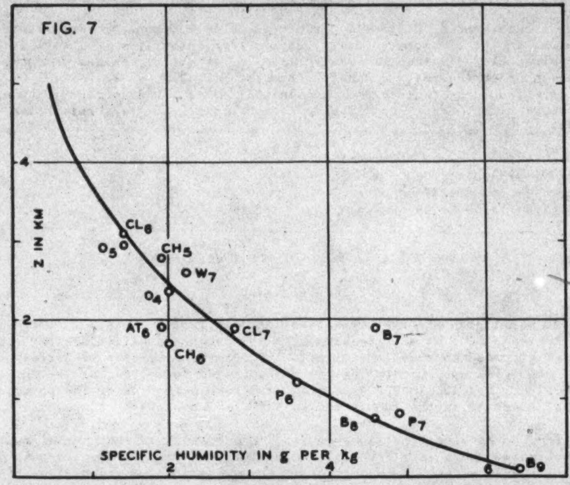


FIG. 7

The effect of this divergence, as previously pointed out, would be to draw closer together the surfaces of constant potential-temperature, thereby reducing the lapse-rate. This diagram definitely shows that spreading (horizontal divergence) of air is far more important in the establishment of stabilizing forces with normal subsidence than the mere sinking of layers with conservation of the mass in a unit column. The divergence of the dotted and solid curves really gives a measure of this stretching.

In order to portray this more effectively, the pressure-difference per degree lapse of potential temperature in the layer above the inversion was plotted against the elevation of the top of the inversion. This is shown in Figure 6. If there were no stretching the graph would be a vertical line, since the number of millibars per unit degree of potential temperature would remain constant. Figure 6 shows that with decreasing height of subsiding layers the pressure-difference between isopotential temperature-surfaces decreases in a linear fashion. This is not yet satisfactorily explained, and until further cases are studied in detail no generalizations can be attempted.

Figure 7 shows the specific humidity at the base of the subsidence-inversion plotted against its altitude. As the inversion reaches lower levels the effect of turbulent exchange becomes more pronounced. Moisture and dust are carried up to the base of the inversion by this process, and because of the marked stability above cannot penetrate the inversion-base. It therefore serves as a boundary for upward transport. This boundary is clearly recognized in aeroplane-flight as a sharp haze horizon, characterized by excellent visibility above and poor below. The concentration at the inversion-base provides a good radiating surface. Due to the high transparency of the upper atmosphere this surface radiates freely to space. In this manner, as well as by the effects of turbulence in the surface-layer, subsidence-inversions often intensify upon reaching low levels. The combination of subsidence- and radiation-effects at low levels in stagnating anticyclones will generally bring about a large diurnal temperature-range, since increased turbulence during the daytime will bring air of potential warmth down to the surface. Furthermore, insolational heating during the daytime will be confined to the lowest layers on account of the low height at which convection is stopped.

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AEROLOGICAL STUDIES ON MOUNT WASHINGTON

S. P. Fergusson

The Mount Washington Observatory, established in 1932 by Joseph B. Dodge of the Appalachian Mountain Club as a contribution to the International Polar Year Program of 1932-1933, has afforded an excellent opportunity for the extension of a study of the influence of mountains upon meteorological phenomena conducted during the summer seasons of 1905, 1906, and 1907. The data are simultaneous records of the principal meteorological elements on the summit and in the free atmosphere at the same height.

Except for the weather-conditions, which are extremely severe, the circumstances of this investigation were very favorable, especially as regards completeness of local records on the summit and at base-stations on the eastern and western sides of the range, transportation, and quarters on the summit. The exacting field-work was made possible only by the generous cooperation and aid of many associates, particularly C. F. Brooks, Director of the Blue Hill Observatory, Messrs. Dodge, Pagliuca, McKenzie, Stephenson, and Stone of the Mount Washington Observatory, Philip Towle of the Mount Wachusett Observatory, and Messrs. Schell and Harmantas of Blue Hill Observatory and the Department of Meteorology, Massachusetts Institute of Technology, which Department also kindly loaned an aeroplane meteorograph and accessories. The cost of the work was met chiefly by a grant from the Milton Fund of Harvard University and in part by Blue Hill Observatory.

Originally, it was planned that the comparative aerological data would be obtained under favorable conditions from meteorographs carried by kites flown from the summit and during calms from similar instruments lifted by captive balloons; but, records of wind-velocity having indicated that calms were too infrequent for the efficient use of the balloon, arrangements were made with the manager of the Twin Mountain Airport for the use of his sight-seeing aeroplane to carry a meteorograph to heights slightly exceeding that of Mount Washington. The work at Twin Mountain, which also included observations of pilot-balloons at least once daily and observations of clouds, was conducted by Messrs. Schell and Harmantas. On the summit there were frequent observations of pilot-balloons and clouds made by the staff of the Observatory, who also assisted Mr. Towle and the author in the routine work of kite-flying. Field-work began July 29 and ended September 15, 1933, with the last observations of pilot-balloons on the summit and the last ascension of the aeroplane at Twin Mountain. During this period, seven ascensions of the kite and about 40 of pilot-balloons were secured on the summit while at Twin Mountain there were obtained eleven ascensions of the aeroplane and more than 50 of pilot-balloons. Excepting the data of winds from pilot-balloons, the records do not cover a wide variety of conditions; kites could be flown only during the very short periods when the velocity of the wind was changing from too high to too low or vice versa, and, especially during August, the danger from thunderstorms was considered too great to justify ascensions during densely foggy weather which prevailed during about one half of the period available for the work. It is believed, however, that complete analysis of the data will indicate methods of allowing for the more important effects of the mountain and of improving exposures of instruments not only on Mount Washington but on other peaks.

Concerning instruments, the kite-meteorograph was one of several in use at Blue Hill when regular ascensions were discontinued in 1913, improved by the addition of a very sensitive thermometer of thermostatic metal having a scale of 5 mm for 1° C and the substitution of a new and more accurate three-cup anemometer for the four-cup type hitherto in use. Following the technique employed at Blue Hill, the recording mechanisms of the meteorograph were secured to the lower rear edge of the front cell of the kite while the anemometer, connected detachably with the recording mechanism, projected in front of the kite where it was freely exposed to the wind. The meteorograph was held rigidly in a wooden frame by a single pin and could be attached or detached within a few seconds--a feature of importance during high winds when accidents are difficult to avoid. The aeroplane meteorograph was of the type regularly used in the daily ascensions at Boston by the Department of Meteorology of Massachusetts Institute of Technology and sufficiently sensitive to record the rapid changes of condition likely to occur near the mountain.

The kite was of the Clayton-Hargrave type. The parts of the frame were united by castings in such a manner that any broken stick could be replaced immediately without disturbing other parts and the entire kite could be folded for shipment within a few minutes. This feature was found to be very useful on the rough surface of Mount Washington where a stick was broken almost every time the kite landed. The lifting surface of the kite was 6.6 square meters and the specific weight about 650 grams per square meter of lifting surface. At sea-level this kite will fly in a wind of four meters per second but on Mount Washington, where the density of the air is about 20 per cent lower, it was found that, due to the greater variability of the wind, it was difficult to maintain the kite in the air if the velocity fell below 8 m/s. During high winds, however, conditions were better and the kite could be pulled down to one's hand without serious risk; on September 13, it was landed during a velocity of 23 m/s or 50 miles an hour.

The reel for flying the kite was a heavy double-flanged iron pulley 33 cm in diameter on which was wound a line of No. 11 music wire 2500 meters long, the length of which was registered on a suitable counter. This (pulley) storage-drum was mounted in a heavy wooden box secured to a central pivot so that the reel was adjustable to changes in the direction of the wind. Reeling out and reeling in the line were controlled by a strap brake and opposite crank-handles. Usually the "pull" of the kite was less than 15 but, during high winds it exceeded 25 kilograms and two men were needed to handle the kite when it was landed. The greatest length of line employed was 1450 meters.

The heights attained by the kite were seriously affected by the downward movement of the wind on the leeward side of the summit. Ordinarily with a short line the kite would maintain an altitude of about 54° to 58°; but, generally, even during high winds, the altitude seldom exceeded 30° with less than 300 meters of line out. The maximum height attained was 495 meters with 1400 meters of line and there were several maxima of about 300 meters.

Some of the more important results obtained so far are:

(1) Evidence that the surface of the cone of Mount Washington (the upper 400 meters) during clear weather becomes over-warmed even when the wind-velocity approaches 10 m/s, and temperatures registered on the summit within a few meters of the surface are too high; a short distance above, the effect of mechanical cooling of the air driven up the slope becomes conspicuous and the apparent lapse-rate within 10 to 20 meters of the ground is very large. During midday when the velocity of the wind is moderate or high, the temperature recorded on the summit is generally lower than it is in the free air at the same height; when the velocity is low the temperature of the free air is lower than that recorded on the summit. These different conditions are shown in Table 1 by the comparison of data obtained by means of kites in 1905-1907 during relatively strong winds with similar data secured in 1933 by means of the aeroplane when the velocity was much lower.

(2) During light winds, perhaps because of strong convection near the surface, the mean velocity is smaller on the summit than in the free atmosphere (see Table 1); during strong winds (12 m/s or higher) the velocity on the summit is much higher than that in the free atmosphere.

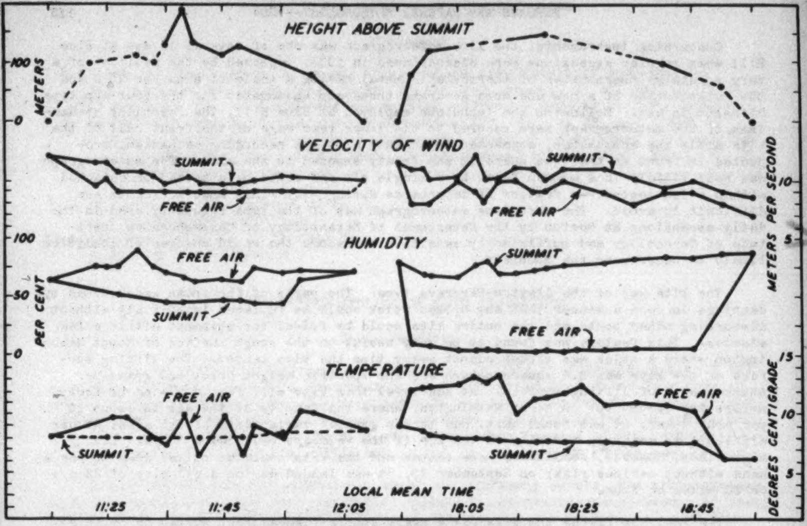

FIG. 1—CONDITIONS ON AND ABOVE MT. WASHINGTON DURING TWO KITE ASCENSIONS, AUGUST 30, 1933

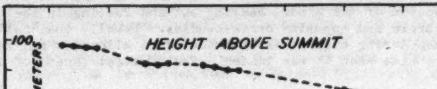

FIG. 2—CONDITIONS ON AND ABOVE MT. WASHINGTON, SEPTEMBER 13, 1933

Table 1--Temperature and wind on Mount Washington (1913 meters) and in the free atmosphere (1913 meters)

Date and time	Temperature			Velocity of wind	
	Summit	Free air	Difference	Summit	Free air
	°C	°C	°C	m/s	m/s
			By kite from Twin Mountain		
1905, Aug. 24, 17:43	6.1	8.3	-2.2	16	14
1907, July 18, 18:30	13.3	13.2	+0.1	12	10
21, 13:30	5.8	6.6	-0.8	24	16
26, 16:50	10.3	9.1	+1.2	22	15
28, 12:37	6.8	6.9	-0.1	18	11
			By aeroplane from Twin Mountain		
1933, Aug. 10, 10:30	8.5	4.5	+4.0	5	3
10, 14:25	10.4	6.0	+4.4	4	5
16, 17:18	12.7	10.6	+2.1	10	6
17, 14:10	13.2	10.9	+2.3	6	4
21, 11:55	9.9	10.5	-0.6	0	4
22, 13:55	14.6	11.6	+3.0	2	3
23, 11:27	14.4	13.3	+1.1	5	5
29, 14:55	7.1	5.2	+1.9	5	8
31, 11:50	12.4	10.4	+2.0	3	1
31, 15:50	12.1	8.9	+3.2	3	4
			At kite, 125 meters above summit		
1933, Aug. 7, 15:21	13.2	10.4	+2.8	13	12
14, 15:40	7.2	5.5	+1.7	15	..
30, 11:48	9.0	8.1	+0.9	10	9
30, 18:35	7.4	11.0	-3.6	10	9
1933, Sep. 6, 13:58	8.0	8.4	-0.4	15	13
8, 10:30	9.4	9.9	-0.5	11	12
13, 15:07	3.8	4.5	-0.7	14	17
			At kite, 50 meters above summit		
1933, Sep. 13, 17:35 to 17:55	5.1	3.4	+1.7	18	22

(3) The acceleration of the wind over the summit decreases rapidly within a short distance; this is shown very clearly in Figure 2, when the kite-meteorograph was kept at a height of only 50 meters above the summit for a period of 25 minutes. Other records indicate a decrease of velocity at heights exceeding 100 meters and a tendency toward the usual increase of velocity at greater heights.

(4) Very sharply-defined contrasts between conditions at the surface and a short distance above sometimes persist for periods exceeding an hour. Referring to Figure 1, on August 30, 1933, between 11 a.m. and noon at a height of 90 to 195 meters the average humidity in the free air was between 65 and 88 while on the surface it ranged between 44 and 64; during a second ascension to approximately the same height between 5:15 and 7:00 p.m. the conditions were reversed; about 90 meters the humidity fell nearly to zero while on the surface it had risen, since noon, from about 50 to 80 per cent. During both ascensions the temperature and wind, respectively, were higher and lower in the free air than on the surface.

(5) It seems probable that instruments exposed on a tower 50 meters high would be above some of the larger effects of the mountain and that corrections can be determined, at least for those that persist during a considerable period of time. As stated, the data available concern a limited variety of conditions and chiefly the afternoon when the temperature on the summit is nearly the same as it is in the free atmosphere. At night, it is decidedly lower, perhaps more than 5° C lower, while the temperature of the free atmosphere remains nearly constant throughout the 24 hours.

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DIFFERENCES BETWEEN TEMPERATURES, HUMIDITIES, AND WINDS ON THE WHITE MOUNTAINS AND IN THE FREE AIR

Irving I. Schell

The influence of mountains on the air passing over them can be determined by comparing the meteorological elements in such a region with those of the free air. The nature and extent of the influence depends largely on the time of day, the season, the type of synoptic air-mass, the height of mountain range or plateau, and its characteristic topography.

For the aviator, mountain regions create a special problem. In encountering air-currents with temperature and moisture different from those prevailing elsewhere, he is often exposed to the danger of ice-formation on the aeroplane. He also has to contend with variable ceilings and strong winds, often with considerable vertical components.

But aside from offering information on the weather over the mountains, mountain observations afford a means for giving a helpful picture of conditions prevailing in the atmosphere at points not far removed from the mountains, provided the same air-mass covers the whole region. After allowing for the differences, which are primarily a function of air-mass and height of mountains, a fair representation of meteorological elements in the free air can be obtained. This method is of great value because a continuous record is afforded.

The present paper forming one of a group intended to explain and establish the differences between meteorological elements on mountains and in the free air, deals with an investigation of these differences in the White Mountains, conducted by the author, as a part of a project for the study of mountain meteorology, carried out last summer by Harvard University, under the direction of S. P. Fergusson of Blue Hill Observatory, and with the cooperation of the Mount Washington Observatory and the Meteorology Course, Massachusetts Institute of Technology. Temperatures, lapse-rates, humidities, and winds prevailing in the vicinity of the Presidential Range were compared with those of the free air over the Ammonoosuc Valley. From the observed differences several conclusions of especial interest are drawn here.

The observations were supplied by several mountain stations located at different heights. The highest is the fully equipped Mount Washington Observatory, situated on the summit of Mount Washington, at 1915 meters above sea-level, and 1489 meters above the floor of the valley. Continuous records of pressure, temperature, and humidity were also obtained at Greenleaf Hut on Mount Lafayette, 1250 meters, and at Base-Station (Mount Washington), 790 meters, and Twin Mountain (Valley Town), 427 meters; regular observations of wind-velocity and sky-cover were also made at the last station. Several other stations of intermediate elevations provided observations of temperature at 8:00 a.m., 12:00 noon, and 8:00 p.m. These records were compared with meteorograph-records obtained with an aeroplane flying from Twin Mountain, in the Ammonoosuc Valley, a point 16 km west of Mount Washington and lesser distances from the other stations. The period studied comprises the month of August and part of September, 1933. The differences in temperature, relative humidity, and wind-velocity were calculated, with greater weight given to those stations where continuous records were supplemented with observations. The method used in determining these differences was to compare simultaneous readings of the various elements along the slopes with those of the free air at the same levels over the valley. The differences were averaged, curves being drawn in some instances to indicate the characteristic relationships.

During a clear night, the mountain tops and slopes cool more rapidly than the air in the free atmosphere at the same level. Soon after the air on the slopes reaches a lower temperature than over the valley the cooling is somewhat retarded owing to the sinking of the cold air and its replacement by the adjacent warmer air at the same level [see bibliography, reference 1]. If the weather is windy there may be no settling, but an ascent, which makes the cooling more intense, being roughly directly proportional to the strength of the wind, in which case the fall in temperature is caused by the adiabatic cooling of the air forced up the mountain, as well as by the loss of heat due to outgoing radiation. During the day the temperature of the mountain, unless covered by snow, will rise more rapidly than that of the air at same level over the valley, and the temperature-difference will be diminished. In the summer, on days with light winds and clear skies, when there is strong insolational heating the temperature on the mountain will often approach a value considerably greater than that of the free air and the temperature-difference is then positive. With cloudy weather incoming radiation through the day and outgoing during the night will be diminished, so that the differences will be less accentuated. The average temperature-difference between Mount Washington and air over the valley at that level was found to decrease with increasing cloudiness on the summit. Thus for a sky-cover of zero to three-tenths, the temperature-difference was 3°.5 C, and between four and seven-tenths, 2°.6 C. No comparisons for days with greater sky-cover were made because aeroplane ascents could not be undertaken.

The relationship between the temperature-difference and sky-cover appears simple, decreasing with increasing cloudiness, as we have seen. However, inasmuch as cloudiness is accompanied by air-masses of varying degree of moisture-content, and lapse-rate, factors in turn having a great influence on the temperature-difference, the actual relationship between the latter and sky-cover is more intricate. On the one hand, a thick cloud-layer will prevent insolational heating; on the other, latent heat of condensation often attending heavy cloudiness may more than compensate for that loss.

The amount of heat of condensation in mountain regions, in addition to being dependent on the moisture-content of the original air and its lapse-rate, varies with the degree of the mechanically forced convection, and hence with the speed of the air-mass and the configuration of the mountains. In general, when saturated air is forced up a mountain, one of the three following possibilities is present. One (exceptional), when the lapse-rate of the free air is equal to the condensation-adiabatic, then the air retains its equilibrium-position; this is the state of compensation. Two, when the lapse-rate is greater than the condensation-adiabatic, then because of the heat liberated the convection is accelerated. Three, when the lapse-rate is less than the condensation-adiabatic, then the air becomes colder than the surrounding air, and the upward convection is retarded. These thermodynamic processes are dependent then on the lapse-rate and moisture-content, as well as on the rate of air-flow and height of range [see reference 2].

The cooling of a wind is in general directly proportional to its velocity. This is, however, true for winds only up to a certain intensity. Thus Peppler [see reference 3], in comparing the temperatures between Zugspitze in the Alps and Lindenberg to the north, finds that with a wind-force of more than 4 Beaufort the temperature-difference ceases to increase. Kleinschmid in a similar study of that region found the average limit to be somewhat greater. It was also found that beyond this limit the temperature-difference reverses its trend. The explanation for this limit as well as for the downward trend is offered by a consideration of the lapse-rate. Very strong winds are usually associated with air of marked instability; in other words, a steep lapse-rate. Under such conditions no cooling is possible. The variation of temperature-difference with the wind is thus greatly dependent upon the lapse-rate. The lapse-rate, in turn, varies much more for different seasons of the year in mountain regions than elsewhere. The air-masses, which are generally of marked stability in the winter, are more stable, especially in the lower layers, in the mountains, owing to the persistent snow-cover prevailing there and to the confining topography. On the other hand, in the summer the generally unstable air acquires a greater instability because of stronger heating at higher elevations [see reference 4]. Lapse-rates of less than half a degree per 100 meters are common in the winter, whereas in the summer they often exceed one degree. Thus marked cooling will result from strong winds in the winter while the cooling effect is inappreciable in the summer. The results obtained in the present investigation, while based on relatively few observations, show that the temperature-difference is independent of the wind-velocity. Low values in temperature-difference were found with winds of 4 Beaufort or more, as well as on days with calms. The wind then exerts no consistent influence on the temperature of the mountains on summer days.

The lapse-rate in mountain regions varies considerably with elevation and, especially in the lower layers, with time of day. In the summer it is steepest near the surface where maximum heating is attained, and decreases with elevation as the effect of convection grows less. It is also steepest in the morning, becoming gentler later in

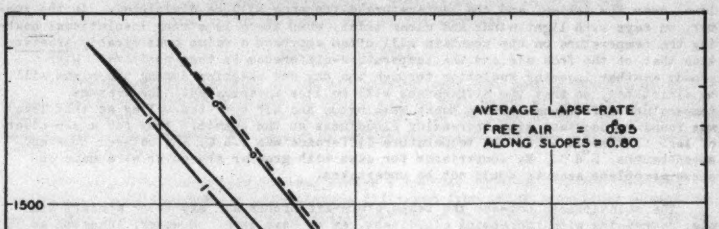

FIG. 1—LAPSE-RATES IN FREE AIR AND ALONG SLOPES

the day as convection increases. The heating on the slopes is considerably greater than in the free air. The lapse-rate in the free air on summer days is therefore steeper than along the slopes. The results obtained show that the average lapse-rate of the free air in the valley up to the height of Mount Washington was 0°.95 C per 100 meters as compared with 0°.80 C along the slopes. In regard to the variation with elevation, it was found that in the lower levels, the first 360 meters above the surface of the valley, the lapse-rate averaged 1°.17 C and in the next layers it was 0°.97 and 0°.82 C per 100 meters. Along the slopes it varied little with elevation, being somewhat greater in the lower layers (see Fig. 1).

The temperature-difference, which, of course, is zero at the bottom, begins to increase with elevation first very rapidly owing to the strong heating at the surface of the valley and then more slowly in the upper layers. In Figure 2, the curve, showing the temperature-difference, is dashed in the lower layers to show that the values are approximate, since no intermediate stations were located between the valley and Base-Station. The highest value for the average temperature-difference is 2°.60 C attained at the level of Mount Washington. Beyond that the temperature-difference sharply decreases. As shown by Figure 2, the temperature-difference increase with elevation obeys a linear relationship except in the lower layers. Thus a fair estimate of the temperature in the free air can be obtained from observing along the slopes. The lapse-rate, which as we have seen is fairly constant on the mountain, can be determined by measuring the temperature at two points along the slope; then by subtracting the differences corresponding to the various levels the lapse-rate in the free air can be computed. It should be kept in mind, however, that the differences can be but roughly determined, and that they vary considerably with general conditions, as discussed above.

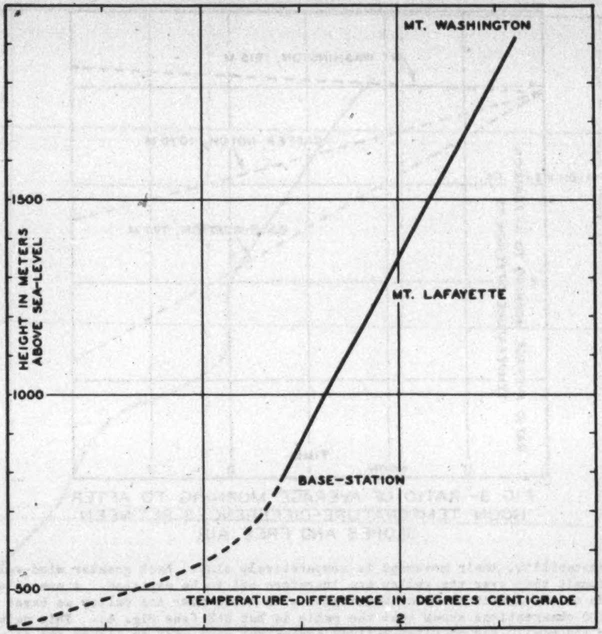

FIG. 2—TEMPERATURE-DIFFERENCE, SLOPE MINUS FREE AIR

The time of the day is an important factor in the consideration of the temperature-differences. On clear days the mountain slopes become rapidly heated in the morning. Thereafter they experience a small gain in temperature. The air in the valley, on the other hand, attains its greatest increase towards the afternoon. In the upper levels, where the temperature-amplitude is small, the increase in the afternoon is roughly the same as the past midday increase on the slopes, so that the temperature-difference remains the same during the day. With decreasing elevation, as the rate of heating of the free air gradually increases owing to the closer proximity to the ground, the temperature-difference falls off towards the afternoon. Accordingly, the rate of decrease of the temperature-difference towards the afternoon is a function of the distance of the level from the surface. Figure 3 shows the ratio of the morning to afternoon temperature-difference for Mount Washington to be roughly one. For the lowest station it is 3.3 while for an intermediate station it is 1.5. The lapse-rate in the lower level was found to decrease from 1°.4 C per 100 meters in the morning to 1° C in the afternoon.

After encountering the mountains, the air in seeking an outlet through the passes has its speed accelerated, but not sufficiently to allow all the air to pass through. It therefore piles up until it reaches the height of the barrier. The extent of the mechanically forced convection depends very largely on the configuration of the mountains and in part on the stability of the air-mass. Stable air will resist the "pushing from below" and once displaced strive to settle back to its original position, while unstable air upon being given the initial impulse will continue to rise and flow over the obstacle. While the air-masses in the summer are generally characterized by

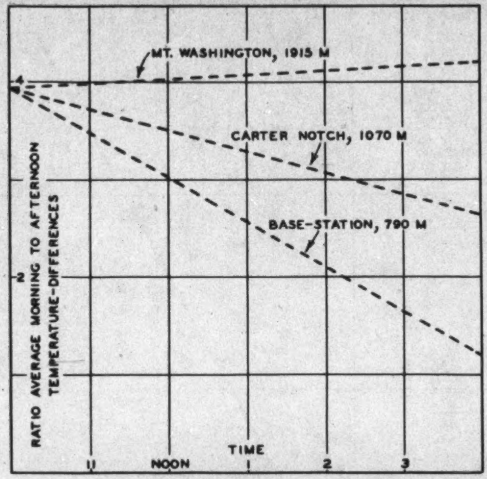

FIG. 3—RATIO OF AVERAGE MORNING TO AFTERNOON TEMPERATURE-DIFFERENCES BETWEEN SLOPES AND FREE AIR

marked instability, their movement is comparatively slow. Much greater wind-velocities on the summit than over the valley are therefore not to be expected. A comparison of the winds on the summit of Mount Washington with those over the valley as based on nearly 100 observations shows that the ratio is but 3:2 (see Fig. 4). This value is probably too small, for no pilot-balloon ascensions were made on cloudy and rainy days during which as a rule the wind is strong.

The relationship between the relative humidity on mountains and in the free air is a complicated one owing to the number of factors involved. Because of the higher temperature during the day and lower in the night, the relative humidity on the mountain should necessarily be smaller and larger, respectively, than in the free air, the difference varying with height and time of day. However, the temperature-difference is responsible for the mountain and valley winds, which greatly influence the relative humidity on the slopes. Along these, during the day, a movement of air from below takes place. The current, which is rich in moisture, raises the relative humidity considerably on the mountain and above it. To a lesser degree, the reverse is true at night when the air begins to flow downward. Mountain tops, especially, show this effect. Early in the morning, before the valley wind is established and when the temperature on the summit is low, the relative humidity was found to be very low, while in the afternoon with a much higher temperature the value was much greater, steadily increasing with the development of the valley wind, and giving rise to clouds, absent in the morning.

Summary

The relation between temperature, relative humidity, and wind-velocity on mountains and the free air on summer days is discussed and roughly determined. It was found that

(1) The wind exerts no consistent influence on the mountain temperature in the summer.

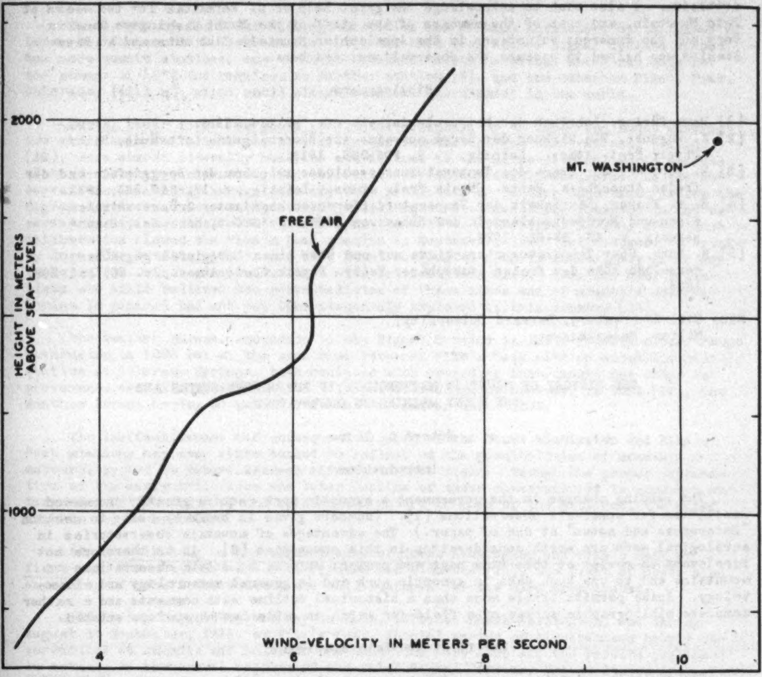

FIG. 4—WIND-VELOCITY IN THE FREE AIR VERSUS THAT ON MT. WASHINGTON

(2) There is a general decrease in temperature-difference with increasing cloudiness; the actual relationship is more complicated owing to other factors involved, such as the lapse-rate and moisture-content of the air.

(3) The lapse-rate in the free air is greater than that along the slopes and is steepest in the lower layers, while along the slopes it is fairly constant; further, it is steepest in the morning, decreasing rapidly towards afternoon with decrease in elevation.

(4) The temperature-difference increases with elevation at a constant rate except in the lower layers, where the increase is more rapid.

(5) The wind over the summit is greater than over the valley by a relatively small value, for, though the air-masses are of marked instability, they are characterized by slow movement.

(6) The relative humidity on the mountain is greatly influenced by mountain and valley winds, and is therefore low in the morning and high in the afternoon.

I am indebted to S. P. Fergusson for his guidance while I was assisting with the project, to C. F. Brooks, without whose aid, encouragement, and helpful suggestions this investigation would have been impossible, and to H. C. Willett for his helpful criticism. I also wish to acknowledge the great help of C. Harmantas for two weeks at Twin Mountain, and that of the members of the staff of the Mount Washington Observatory and the numerous volunteers in the Appalachian Mountain Club huts and at Base-Station who helped to procure the observations used here.

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THE HISTORY OF MOUNTAIN METEOROLOGY IN THE UNITED STATES AND THE MOUNT WASHINGTON OBSERVATORY

Robert G. Stone

Introduction

The pending changes in the government's synoptic work require greatly increased facilities for upper-air observations [1]. (Numbers given in brackets refer to section "References and notes" at end of paper.) The advantages of mountain observatories in aerological work are worth consideration in this connection [2]. It is therefore not irrelevant to review at this time past and present efforts to obtain observations on mountains and to use such data in synoptic work and in general meteorology and climatology. Space permits little more than a historical outline with comments and a rather complete bibliographic survey of a field for which no guide has heretofore existed.

The first mountain stations

The earliest extensive series of meteorological observations taken on an American mountain-top is probably that made by one Nathaniel Noyes for the Smithsonian and Patent Office meteorological system at the new summit hotel on Mount Washington, New Hampshire, (1915 m), during the summer months of 1853 to 1859 [3].

Until 1870 fear of the elements and practical difficulties checked efforts to occupy this summit through the winter [4]. Prof. C. H. Hitchcock, State Geologist, after sponsoring a "successful" expedition led by his assistant, Prof. J. H. Huntington, to the summit of Mount Moosilauke, New Hampshire, (1466 m), from December, 1869, through February, 1870 [5], was able to get the requisite assistance to establish a party, again under Huntington, in an observatory on Mount Washington the following winter.

To this venture the Chief Signal Officer contributed telegraph wire, meteorological instruments, and a trained observer, in return for which reports were wired daily to the Signal Service in Washington. Observations began November 13, 1870 [6]. Though highly ridiculed by the public, the results greatly impressed scientists. During May, 1871, the Signal Service undertook complete responsibility for the observatory and put it on a permanent basis. This was the first well-equipped mountain station in the world and led to the establishment of other summit stations soon afterward.

Some fragmentary observations probably were made on other mountains before 1870, but the only series of any consequence known to the writer is that for Lookout Mountain, Tennessee, from 1866 to 1872 [7].

Mount Washington and Pike's Peak--1870-1894

Encouraged by the Mount Washington station and perhaps influenced by the pleas of Leverrier for mountain observatories [8], the then progressive Signal Service opened two more summit stations, one on Mount Mitchell, North Carolina, which ran only for the summer of 1873 and requires no further mention [9], and the other on Pike's Peak, Colorado, (4311 m), which until closed remained the highest in the world.

During their first few years' existence--roughly, up to 1880--the Mount Washington and Pike's Peak stations, of similar instrumentation and observational routine [10], were almost literally headline attractions in the meteorological world because of their priority, elevation, and observations. But gradually thereafter as the observations apparently became less and less productive of further important results the Signal Service and meteorologists in general manifested declining interest in the observations and eventually in the stations themselves. The Signal Service after much deliberation closed the Pike's Peak station in September, 1888 (but reopened it briefly August to October, 1889), and kept Mount Washington open in summer only after September, 1887. Such a denouement met with criticism and dismay from the many scientists who still believed the potentialities of these sites and of mountain observatories in general had not yet been adequately explored in this country [11].

The Weather Bureau, successor to the Signal Service in 1891, finally closed Mount Washington in 1892 but at the same time reopened Pike's Peak with an excellent base-station at Colorado Springs, both equipped with recording instruments and other improvements over the former station. It was closed again, however, in 1894 [12], the Weather Bureau having no summit stations thereafter until 1898.

The ineffectiveness and consequent closing of the Mount Washington and Pike's Peak stations has ever since tended to reflect on the possibilities of mountain meteorology and to retard renewed efforts in that field. Though the proper explanation of the early brilliance and later decline of these observatories is somewhat embarrassed by the indirect and opinionated nature of much of the evidence, the chief factors may be specified.

(A) Contributing to the significance of Mount Washington and Pike's Peak at first--(1) The stations were well exposed and situated [13], the first of their kind anywhere, of notable elevation, and well equipped for the time when opened.

(2) During May, 1872, and May to June, 1873, at Mount Washington, and during August to September, 1874, at Pike's Peak, special series of simultaneous hourly observations at summits and bases of the mountains were made and the results published *in extenso* in the annual reports of the Chief Signal Officer, United States Army, for 1873-75 and 1882. These observations, first of the sort available, appeared at the time when the leading meteorologists were still necessarily trying to deduce the structure of storms and of the atmosphere in general from surface-observations alone. In the next few years Hann, Hellmann, Woeikoff, Pernter, Köppen, Loomis, Hazen, and others were able to make fundamental or important contributions to meteorology and climatology with the aid of these observations [14].

(B) Contributing to the eventual ineffectiveness and closing of Mount Washington and Pike's Peak--(1) Time and again many of these meteorologists urgently requested the Signal Service to continue hourly observations at summit and at base as a regular routine [15], since such records would have been of the utmost value at that time. This was not done, however, and such records as were regularly kept were insufficient in various ways for purposes of research and consequently relatively unproductive [16]. Furthermore, but few other special investigations or observations were ever carried out at the mountain stations [17]. Since, except for brief exceptions, there were no stations at the immediate bases of the mountains, the unsatisfactory method of comparing the summit-observations with those taken at low elevations 15 to 100 miles away generally had to be resorted to, and with indifferent results [18]. Finally, in 1888 and during 1890-92 at Mount Washington and during 1892-94 at Pike's Peak recording instruments were used and Pike's Peak was given an excellent base-station; but in the meantime, since 1875, a number of high summit stations with base-stations and recording instruments had been opened in Europe and these were already accumulating a large mass of the type of data most valuable to meteorologists [19].

(2) The Signal Service apparently had hoped to find a means to improve forecasting by use of three telegraphic observations a day from the summit stations. This also had been the plan of the Smithsonian Institution and the Hitchcock-Huntington Expedition when the first Mount Washington stations were conceived. The Signal Service, however, holds the honor of being first actually to try this (1870), but the telegraph-lines were very difficult to maintain, that to Pike's Peak being perforce abandoned in 1882, and after many years' trial no improvement therefrom in forecasts could be claimed, so the stations were given up [20].

(3) In view of present-day knowledge, we can say that the Signal Service failed in its efforts to use mountain observations in synoptic work, for lack of a suitable hypothesis with which to interpret the relations between the fluctuations of the elements at high levels and those at low elevations [21]. At the same time, it made a mistake in disregarding the demand for hourly observations or continuous registrations at both summits and immediate bases of the mountains; for this a lack of funds and a conservative attitude towards pure research may perhaps be blamed.

(4) The Signal Service has been criticised for not publishing the observations *in extenso*, which, though certainly a sound reflection, was not an important reason for the ineffectiveness of the mountain stations because the observations for the most part were inadequate anyway. Since the time Prof. Pickering published the 1874-88 Pike's Peak observations *in extenso* in the Harvard Observatory Annals for 1889, no very significant discussions (indeed few of any kind) have resulted therefrom.

The outcome of the Signal Service work in mountain meteorology was all the more unfortunate because in the two decades after 1870 scientists and the public manifested a keener interest in the establishment of mountain meteorological stations than ever before or since; but inasmuch as a private party could not as a rule support a station alone, the Signal Service was frequently asked to set up or help set up and operate mountain observatories, as European governments were then doing, but to no avail [22]. However, the fine observatory on Blue Hill, Milton, Massachusetts, was established by A. L. Rotch, an amateur meteorologist, in 1885 [23].

1894-1932

Mountain meteorology has flourished increasingly in Europe since 1879 while in this country it has waned and waxed rather fitfully. Since Mount Washington and Pike's Peak were abandoned, some excellent mountain observatories have come and gone but continuous records to date have been kept only at the Blue Hill Observatory of Harvard University [23], and at the Lick (Astronomical) Observatory, Mount Hamilton, California [24]. Some meteorological observations have been taken at the astronomical observatories on Mount Lowe and Mount Wilson, California, since about 1896 and 1904, respectively [25]. The Weather Bureau operated first-order stations on Mount Tamalpais, California, from September, 1898, to the end of 1922 ([26], and on Mount Weather, Virginia, from November, 1904, through 1913 [27], the latter primarily an observatory for research. From July, 1903, to April, 1908, several McGill University professors privately subsidized observations on Mount Royal, Montreal, Canada [28], and the University of Nevada sponsored the Mount Rose Observatory (a meteorograph-station) on the crest of the Sierra Nevada from 1906 to about 1919 [29]. In 1909 the Philippine Weather Bureau opened the Mirador Observatory on a hill above Baguio at 1512 m [30]. The Volcano Observatory at 1213 m on Kilauea Volcano, Hawaii, has also been taking some meteorological observations [31].

In this period (1894-1932) upper-air observations played a greatly increasing role in various phases of meteorological work, but mountain observatories have had to stand comparison with balloons, kites, and lately aeroplanes, all of which possess well-known superior advantages in certain respects. Because of the discrepancy between the conditions on a summit and in the free air at the same level away from the mountain there has developed a disinclination to use mountain stations for strictly aerological purposes, in spite of some attempts to determine and allow for the discrepancy [32]. Efforts at Mount Tamalpais, Mount Royal, and Mount Rose to discover means of using summit observations in forecasting did not give very practical results. These circumstances coupled with a general lack of interest in mountain climatology serve to explain the tendency to give up mountain stations in the last two decades.

Miscellany

However, mention of these more or less enduring stations hardly hints at all to the work done in America in mountain meteorology and climatology. To complete the review, attention should be called to the scattered series of special and limited observations of more or less meteorological nature made during short expeditions on high peaks as well as to certain more general investigations.

From July, 1873, to January, 1874, the Hayden Surveys took observations at the summit of Mount Lincoln, Colorado (4305 m), and at Fairplay (3016 m) and Canon City (1625 m) as base-stations [33]. E. S. Holden of the United States Naval Observatory led numerous trips of brief duration in the years, 1873, 1881, 1883, 1885, 1886, and later, to various high peaks and valleys of the Colorado Rockies for the purpose of determining the visibility conditions at possible sites for an astronomical observatory [34]. Dr. Henry Draper made similar observations for the Harvard College Observatory during August and September, 1876, in the Colorado Rockies and the Wasatch Mountains of Utah and Wyoming [35]. The Harvard Observatory sent another expedition of this type to high peaks in Colorado and southern California in the summer of 1887 and winter of 1888-89 [36]. The famous bolometric expedition of Dr. S. P. Langley in 1881 to Mount Whitney, California (highest point in United States), which resulted in a drastic revision of the solar constant, necessarily took meteorological observations [37]. During the summers of 1889, 1890, and 1891 the Weather Bureau operated stations on Mount Killington, Vermont, and Green Mountain, Mount Desert Island, Maine [38]. Brief series of observations were made some time before 1890 on Mount Mansfield, Mount Wooster, and Mount Anthony, Vermont, and on Bear Mountain, Massachusetts [39]. The Campbell-Abbot astronomical expedition to Mount Whitney, California, in 1909, included A. McAdie, who gathered meteorological data [40]. In the summers of 1905, 1906, and 1907 S. P. Fergusson of the Blue Hill Observatory made observations on the summit of Mount Washington, New Hampshire, simultaneous with kite meteorograph-ascents from a nearby valley to determine the difference between summit and free-air conditions [41]; in the summer of 1933 he made kite-ascents from the summit simultaneous with aeroplane meteorograph-ascents from the valley by I. I. Schell to determine the height to which the effect of the mountain extends into the free air above [42]. A. Angström made an expedition to Mount Whitney, California, in August, 1913, to study radiation balance in the atmosphere, the Weather Bureau cooperating by sending up free balloons from Avalon, and captive balloons from Mount Whitney and Lone Pine, at its base [43]. The solar-radiation measurements and magnetic and atmospheric-electric observations of the various observatories of the Smithsonian and Carnegie institutions on peaks in California, Arizona, New Mexico, North Carolina, and South America are well enough known [44]; but little systematic meteorological work has been done at these stations and at the high astronomical observatories in this country [44] because the influential geophysical and astronomical institutions in America have not been much interested in meteorology as an end in itself. The Weather Bureau has had a number of cooperative stations located on or high up on slopes near summits, the records from which may be of some value to mountain meteorology [45].

All the general, local, and special studies in American mountain meteorology and climatology are far too numerous to point out seriatim here. There are many short notes and articles in the literature, largely descriptive and of limited or historical interest only, much of which appears incidentally in geographic, travel, historical, and other scientific writings [46]. Ecologists studying zones of mountain vegetation have obtained considerable meteorological or climatological data for their particular purposes [47]. Classic or fundamentally significant works with more or less bearing on the subject in review and not specifically cited above would certainly include F. H. Bigelow's "Barometry of the United States---" for its discussion of the western Plateau region [48], the study of "Thermal belts and fruit growing in North Carolina" by H. J. Cox [49], and R. DeC. Ward's "Climates of the United States" wherein a vast amount of literature is summarized [50]. Peattie recently discussed some contributions to mountain climatology by American authors [51].

In general, the large though scattered mass of mountain observations taken in America has been utilized to but a small extent of its potential scientific value, though much of it is also now of little use. Much effort has virtually been wasted, owing to failure or inability to select well-exposed sites, to apply adequate instrumentation and observational routine, to use good base-stations, and to publish the records in sufficient detail and in a convenient form and place.

Mount Washington reoccupied

The second International Polar Year Commission's appeal for cooperation through the establishment of mountain stations coincided with Joseph B. Dodge's cherished ambition to reoccupy the summit of Mount Washington for meteorological purposes with the result that in November 1932 the present Mount Washington Observatory was opened under private auspices [52]. At this institution, with the cooperation of the Blue Hill Observatory of Harvard University, the Meteorology Course of the Massachusetts Institute of Technology, the General Radio Company, the United States Weather Bureau, the Eppley Laboratories, Inc., and others, strenuous efforts are being made to overcome the peculiar difficulties of taking observations on a high mountain and to solve the special problems involved in interpretation and use of the observations in synoptic and other meteorological work [53]. While much remains to be done in this direction, the progress thus far has convinced the sponsors and cooperators that such a station can give a continuous record of the upper-air conditions adequate for purposes of research as well as current reports of decided practical value in synoptic work [54]. In regions where very frequent upper-air observations are desired and the suitable mountains exist, summit stations should prove more practical and economical than aeroplanes [55]. It is hoped the Weather Bureau may soon be able to take over Mount Washington and establish a net of mountain stations.

Revival

The Polar Year Commission and the Mount Washington Observatory have revived interest in mountain stations in this country; the Blue Hill and Mount Washington observatories are trying to further that interest in both scientific and popular circles. In cooperation with them, the huts of the Appalachian Mountain Club and of the Dartmouth Outing Club in the White Mountains are attempting to take regular weather-observations during the summer months, when they are staffed. Prof. J. W. Goldthwait of Dartmouth College has, since 1928, enlisted the cooperation of the New Hampshire State Highway Department in establishing nearly a hundred new rainfall stations throughout the state, many on and in the mountains [56]. Frank B. and Philip A. Towle, of Holden, Massachusetts, have, since March, 1933, been operating an automatic meteorograph station on Mount Wachusett, Massachusetts (615 m), in conjunction with a base-station (Avery Hill Observatory) nearby in Holden (280 m) [57]. There are considerable possibilities for extending the taking of observations on mountains through cooperation with such private organizations and interested individuals if the proper encouragement and assistance is given them. The astronomical and astrophysical observatories and solar-radiation stations at high altitudes should be induced to take adequate meteorological observations where they do not already do so.

References and notes

[1] Bull. Amer. Met. Soc., v. 14, pp. 273-281, 1933.

[2] Rossby, Willett, Brooks, Bjerknes, and others, Memorandum on the importance of meteorological mountain observatories----, to be published in Bull. Amer. Met. Soc., v. 15, April, 1934.

[3] Tri-daily pressure, temperature, wind, clouds, precipitation; complete records on file at Weather Bureau, Washington; means of temperature in Smithsonian Inst. Cont. Knowl., No. 277, Smithsonian Misc. Collect., v. 21, p. 53, 1876; of precipitation in Bull. W, 2nd ed., U.S. Weath. Bur., Sect. 105, p. 5; discussion of temperature observations by Nathaniel Noyes: Temperature of the weather of the summit of Mount Washington, pamphlet of about 50 pp., Portland, Me., 1854.

[4] F. W. Kilbourne, Chronicles of the White Mountains, pp. 305-311, N.Y., 1916; C. H. Hitchcock and others, Mount Washington in winter, pp. 1-4, Boston, 1871.

[5] Kilbourne, reference [4], pp. 311-314; J. H. Huntington, Proc. Am. Assoc. Adv. Sci., Troy Meeting, 1870; Hitchcock and others, reference [4], pp. 5-6, 87-100.

[6] History, journal, and meteorological observations of expedition detailed by Hitchcock and others in reference [4]; also briefly by Kilbourne, reference [5], pp. 314-330 (somewhat inaccurate); and in C. H. Hitchcock, Geology of New Hampshire, v. 1, pp. 59-118, 119-146, Concord, 1874.

[7] Observations (temperature and precipitation) on file at Weather Bureau, Washington; elevation 496 m; a U.S. Weather Bureau cooperating station at 760 m November, 1888, to October, 1889, and at 655 m 1914 to 1920, means published in Climatological Data, U.S. Weath. Bur., and Bull. W, 2nd ed., U.S. Weath. Bur.; Chattanooga, U.S. Weather Bureau station, as base, elevation 239 m.

[8] W. de Fonvielle, The abandonment by the United States of meteorological stations on mountain tops (in French), La Science Illustrée, April 2, 1892; contains many gross errors of fact, however.

[9] 2046 m, highest peak in eastern United States, fine site; observations May 1 to Sep. 5, 1873, at base-station Aug. 1 to Sep. 5; hourly observations summit and base, June to Sep.; observations *in extenso* with comparison data for Knoxville published in Ann. Rep. Chief Signal Officer, U.S.A., 1873, paper No. 16, pp. 770-947; U.S. Weather Bureau cooperating station on summit since 1925, monthly means in Climatological Data, U.S. Weath. Bur.

[10] Observations as of second-order stations taken, except temporarily as noted later, three times daily and telegraphed to Washington; no recording instruments used before 1888 except anemographs, though at Mount Washington it could not be used in winter owing to frost (rime). Instruments used in the 1870's (see Ann. Rep. Chief Signal Officer, U.S.A.): Barometer, thermometer, maximum and minimum thermometers, hygrometer, Robinson 4-cup anemometer, anemograph, small wind-vane, and rain-gage (all of "standard" type).

[11] de Fonvielle, reference [8]; H. A. Hazen, Amer. Met. J., v. 5, pp. 214-217, 1888; A. L. Rotch, Amer. Met. J., v. 8, pp. 396-400, 1892; W. M. Davis, Appalachia, v. 4, pp. 225-244, 327-350, 1886; Amer. Met. J., v. 5, p. 183, 1888.

[12] First-order station; monthly climatological summaries and full observations of pressure, temperature, wind, published in Ann. Rep. Weath. Bur., 1892-93, 1893-94, 1894-95; P. Morrill, Brief discussion of hourly meteorological records at Pike's Peak and Colorado Springs, Nov., 1892, to Sep., 1894, Ann. Rep. Weath. Bur., pp. 215-232, 1895-96, with tables, maps, diagram; A. J. Henry, Variations of pressure and temperature at summit and base-stations in the Rocky Mountain Region, Bull. Mt. Weath. Obs'y, v. 3, pp. 202-225, 1910, and v. 4, pp. 103-114, 1911; A. Woeikoff, Met. Zs., v. 13, pp. 417-419, 1896; S. P. Fergusson, The value of high-level meteorological data in forecasting changes of temperature----, Univ. Nevada Agric. Exp. Sta., Bull. 83 Technical, 1915.

[13] Description and locality of Mt. Washington station--H. A. Hazen, Amer. Met. J., v. 7, pp. 393-394, 1890; G. E. Curtis, U.S. Sig. Ser. Notes, No. 16, pt. 2, 1894; A. L. Rotch, Amer. Met. J., v. 8, pp. 396-400, 1892, contains description of all the early American mountain stations.

[14] Base-station for Mt. Washington (800 m) 3.5 miles west, for Pike's Peak (Colorado Springs, 1859 m) 11 miles east; Mt. Washington series first published in Ann. Rep. Chief Signal Office, U.S.A., 1873 and 1874; Hazen published Pike's Peak series with corrected edition of Mt. Washington series in Ann. Rep., Chief Signal Officer, U.S.A., 1882, pt. 1, append. 73, pp. 897-926, and discusses them. Published discussions of these observations are as follows:

(A) Of both Mt. Washington and Pike's Peak series--J. Hann, Zs. Met., v. 11, pp. 84-90, 1876; Zs. Met., v. 14, pp. 154, 333-349, 1879; Zs. Met., v. 15, p. 238, 1880; Met. Zs., v. 8, pp. 201-220, 1891. A. Woeikoff, Met. Zs., v. 2, pp. 201-218, 1885. E. Loomis, Amer. J. Sci., 3rd Ser., v. 17, pp. 1-25, 1879, v. 18, pp. 1-16, 1879, v. 22, pp. 1-18, 1881, v. 28, pp. 1-16, 1884; Contributions to meteorology. H. A. Hazen, Amer. J. Sci., 3rd Ser., v. 24, pp. 105-113, 1882; Amer. Met. J., v. 6, pp. 463-466, 1890; Ann. Astr. Obs. Harvard College, v. 22, Introduction, 1889 (bibliography and tables of Pike's Peak series also). W. M. Davis, Appalachia, reference [11]. W. Köppen, Zs. Met., v. 14, pp. 333-349, 1879; Ann. Hydrog., v. 11, p. 625, 1883. J. M. Pernter, Zs. Met., v. 20, pp. 321-326, 1885. H. H. C. Dunwoody, Ann. Rep. Chief Signal Officer, U.S.A., 1876, pp. 349-360.

(B) Of Mt. Washington series only--G. Hellmann, Zs. Met., v. 10, pp. 296-301, Nr. 19, pp. 311-316, Nr. 20, 1875; A. Woeikoff, Zs. Met., v. 8, pp. 337-342, 1873; J. M. Pernter, Zs. Met., v. 20, pp. 140-142, 1885; W. W. Rundell, Q.J.R. Met. Soc., v. 2, pp. 217-226, Oct., 1874.

(C) Of Pike's Peak series only--J. Hann, Met. Zs., v. 8, pp. 201-220, 1891; J. Hann, Sitz. könig. Akad. Wiss. Wien, mathem.-naturw. Klasse, v. 103, pp. 1-72, Abth. IIa, 1894.

[15] For example, A. L. Rotch, reference [11]; W. M. Davis, reference [11]; A. Woeikoff, Met. Zs., v. 2, p. 218, 1885.

[16] Monthly climatological summaries of the regular observations published in Ann. Rep. Chief Signal Officer, U.S.A., and Ann. Rep. Weath. Bur. till stations were closed, also in the current Mon. Weath. Rev., and the telegraphic reports (when received) were printed on the daily weather-map bulletins of the Signal Service; monthly summaries for Mt. Washington in Bull. New England Met. Soc., No. 1-34, Nov., 1884, to Aug., 1887; Pike's Peak observations Jan., 1874, to June, 1888,

published in extenso in Ann. Astr. Obs. Harvard College, v. 22, 1889; until 1880 Ann. Rep. Chief Signal Officer, U.S.A., included daily maximum and minimum temperatures and frequency of winds from each direction (observed to eight points only!), after 1879 they included from time to time tables of means of the various elements based on full length of records of the stations up to that time; manuscript daily journal of Mt. Washington station is in Boston Public Library (cat. No. 7960.74); means of precipitation in Bull. W, 2nd ed., U.S. Weath. Bur.; further tabulations and discussions of the regular observations in the following (classified as in reference [14]):

(A) Mt. Washington and Pike's Peak--J. Hann, Met. Zs., v. 8, pp. 183-185, 1891; Wm. Ferrel, Popular treatise on the winds, pp. 125-26, 1889, and Meteorological researches, pt. II, U.S. Coast Geod. Surv. Rep., 1878, pp. 45-47; T. Russell, Amer. Met. J., v. 8, pp. 1-3, 1891; A. Woeikoff, Amer. Met. J., v. 5, pp. 79-83, 1888, v. 7, pp. 543-552, 1891; W. M. Davis, Appalachia, reference [11], and Elementary meteorology, ed. 1894, passim; F. Waldo, Amer. Met. J., v. 6, pp. 223-228, 1889, v. 6, pp. 368, 370, 1889; Zs. Met., v. 25, p. 40, 1890; W. R. Dewey, Amer. Met. J., v. 3, pp. 27-31, 1886; A. L. Rotch, Amer. Met. J., v. 8, pp. 145-158, 193-211, 1891; F. H. Bigelow, Barometry of the United States---, Ann. Rep. Weath. Bur., 1900-01, v. 2; S. P. Fergusson, reference [12]; H. A. Hazen, Amer. Met. J., v. 4, pp. 82-94, 1887, v. 6, pp. 463-466, 1890, pp. 97-107, 1889; H. A. Hazen, J. Frank. Inst., v. 96, pp. 45-52, 1888; H. A. Hazen, Amer. J. Sci., v. 24, pp. 105-113, 1882.

(B) Mt. Washington only--J. Hann, Met. Zs., v. 5, pp. 7-17, 1888; H. H. Clayton, Sci., N.S., v. 17, pp. 10-11, 1891, pp. 66-67, 1891; Amer. Met. J., v. 4, pp. 74-82, 1887; W. Upton, Bull. 2, New England Met. Soc., pp. 3-4, 1884; P. M. Dechrevens, Deuxieme Note, Zi-ka-wei Observatoire, China, 1887; E. Antevs, The Alpine Zone of the Mt. Washington Range, Chap. 3, 1932; H. A. Hazen, Amer. Met. J., v. 5, pp. 214-217, 1888, Mon. Weath. Rev., v. 19, pp. 171, 199, 224, 250, 1891, Sci. N.S., v. 17, pp. 47-48, 1891.

(C) Pike's Peak only--Zs. Met., v. 18, p. 170, 1883; P. M. Dechrevens, Amer. Met. J., v. 3, pp. 170-186, 1886; cf. bibliography by Hazen in Ann. Astr. Obs. Harvard College, v. 22, 1889.

[17] Wm. Ferrel, (on "pumping" of the barometer at Mt. Washington), Ann. Rep. Chief Signal Officer, U.S.A., 1887, pt. 2, pp. 143-144, reported also by F. Waldo in Modern meteorology, pp. 91-93; G. E. Curtis, Effect of wind-currents on rainfall (at Mt. Washington), Sig. Service Notes, No. 16, pt. 2, 11 pp., 1894; H. A. Hazen, Observations and studies on Mt. Washington, Amer. Met. J., v. 7, pp. 393-398, 1890, pp. 461-472, 1891; at Pike's Peak were made some of the determinations of dew-point and vapor-pressure constants at low temperatures used in Marvin's Psychrometric tables, U.S. Weath. Bur., 1900, 1910, 1912, 1915 (see p. 9, ed. 1915).

[18] H. A. Hazen, Mon. Weath. Rev., v. 19, 1891, pp. 171, 199, 224, 250; F. Waldo, Amer. Met. J., reference [16]; E. Loomis, reference [14A]; A. J. Henry, reference [12]; S. P. Fergusson, reference [12]; E. Antevs, reference [16B]; J. Hann, Zs. Met., v. 11, pp. 84-90, 1876; J. M. Pernter, Zs. Met., v. 20, pp. 321-326, 1885. An exception should be noted in case of observations made for six weeks in July to August, 1888, at Mt. Washington, when recording instruments were run at the summit and at both east and west bases while eye-observations were made at eight intervals down the east slope; these observations not published nor discussed except sketchily by Hazen, reference [17].

[19] A. L. Rotch, Amer. Met. J., v. 3, pp. 15-24, 1886.

[20] A. L. Rotch, Amer. Met. J., v. 8, pp. 396-400, 1892; H. A. Hazen, Amer. Met. J., v. 5, pp. 214-217, 1888; S. P. Fergusson, reference [12].

[21] Rossby, Willett, Brooks, and others, reference [2].

[22] From 1870 to 1883 the Signal Service had received requests from private parties to establish stations on about 30 mountains, none of which was ever granted, see list in Ann. Rep. Chief Signal Officer, U.S.A., 1884.

[23] Shortly after being established, affiliated with Harvard University, of which it is now a part. Elevation 195 m, base-station at 64 m, formerly one at 15 m; Observatory is well known for its research activities, particularly for development of aerological work with kites, begun in 1894, for demonstration of practicability and advantages of local forecasting (1886) which resulted in adoption of such methods by the Signal Service, and for one of the earliest intensive studies of cloud-heights and velocities (1890-91, 1896-97); Observatory and its early work well described by F. Waldo, Pop. Sci. Month., pp. 290-340, 1901.

Publications (by the Observatory): Observations, 1886; Blue Hill Obs. Bull. No. 1-3, 1898-1900; Observations and investigations made at Blue Hill Observatory, 1927-29; Clouds, by A. McAdie; Airgraphics, by A. McAdie; Observations and investigations of Blue Hill Observatory, annually or biennially in Ann. Astr. Obs. Harvard College, v. 20 to v. 87, 1887-1926; many researches reported in the meteorological journals. Observatory well equipped and staffed, fine library.

[24] Elevation 1283 m; San José, California, U.S. Weath. Bur. station as base, 43 m; description and early history by E. S. Holden, Smithsonian Inst. Misc. Collect. No. 1035, pp. 49-58, 1886; observations 1879-87 somewhat broken, since then full homogeneous observations to present; complete records for 1880-85 in Pub. Lick. Obs., v. 1; 1880-1893 summarized by C. D. Perrine, Pub. Astr. Soc. Pacific, v. 1, p. 47; detailed history of meteorological work by W. G. Reed, Mon. Weath. Rev., v. 42, pp. 393-445, 1914; means in Climatological Data, U.S. Weath. Bur., and Bull. W, 2nd ed., U.S. Weath. Bur., and Bull. L, U.S. Weath. Bur.

[25] Elevations 1042 and 1783 m, respectively, Pasadena as base-station (cooperating station, U.S. Weath. Bur.), 252 m; both U.S. Weath. Bur. cooperating stations, means in Climatological Data, U.S. Weath. Bur., and Bull. W, 2nd ed., U.S. Weath.Bur.

[26] Elevation 760 m, Weather Bureau stations at San Francisco, Kentfield, Sausalito, and Pt. Reyes as bases; observations in Ann. Rep. Weath. Bur., Bull. W, 2nd ed., Climatological Data, Bull. L; established to assist forecaster at San Francisco; observations first to reveal prevalent summer inversion in this region; special studies of sea-fogs by A. McAdie in Bull. L, and by H. Wright, Mon. Weath. Rev., v. 44, p. 342, 1916.

[27] Elevation 526 m, base-stations at 217 m and 137 m on east and at 152 m on west side (valleys); observations summarized in Ann. Rep. Weath. Bur., and Bull. W, 2nd ed., and Climatological Data; researches published in Bull. Mt. Weath. Obs., 6 vol., 1908-13, include special studies of solar radiation, atmospheric electricity, and much balloon and kite work; station closed for political rather than scientific reasons; since 1913 a cooperating station, U.S. Weather Bureau, means in Climatological Data and Bull. W, 2nd ed.

[28] Elevation 244 m, base at 189 m only 1005 m away; results discussed by C. H. McLeod and H. T. Barnes, Trans. R. Soc. Canada, 2nd ser., 1904-05, Sect. 3, 1906-07, Sect. 3; 3rd ser. 1907-08, Sect. 3, 1908-09, Sect. 3; Mon. Weath. Rev., v. 34, pp. 505-510, 1906; reviewed by S. P. Fergusson, reference [12].

[29] Elevation 3292 m, base-stations at Truckee, California, 1825 m, 30 miles west and at Fallon, Nevada, 1208 m, 60 miles east; object to investigate (1) value of upper-air data in forecasting temperature and frost in fruit-growing valleys of the region, (2) relation of forests to conservation of snow for irrigation, etc., and (3) temperatures of the fruit-growing regions of the state; (1) studied by S. P. Fergusson and reported in Bull. 83 Tech., Nev. Agric. Exp. Sta., 1915; (2) involved the development of snow-surveying by J. E. Church, for which the Observatory is best known, reported by Church in Sci. Amer. Suppl. No. 1914, v. 74, pp. 152-155, 1912, in Geog. Rev., v. 23, pp. 529-563, 1933, in Rep. Comm. Hydr. Snow, Trans. Amer. Geophys. Union, 13th annual meeting 1932, pp. 277-280, and 14th annual meeting 1933, pp. 338-345, in Snow-surveying in relation to forecasting stream-flow (Nev. Agric. Exp. Sta. Monograph of about 400 pp., to be published soon), in Snow-surveying---(J. Agric. Res., to be published soon); (3) is discussed in Bull. 79, Nev. Agric. Exp. Sta. Observatory was abandoned as a meteorograph station about 1919 but is still used as base for snow-survey operations; snow-surveying now carried on by cooperation of various agencies throughout the mountains of the West and to some extent in the Appalachians. Other reports on the work of the Observatory by J. E. Church, Jr.: Bull. 67, Nev. Agric. Exp. Sta., 36 pp., 1908; Mon. Weath. Rev., v. 34, pp. 255-263, 1906; Appalachia, v. 11, No. 3, pp. 239-248; Sierra Club Bull., v. 6, pp. 177-185, 1907; Mon. Weath. Rev., v. 35, pp. 578-579, 1907; Sci., N.S., v. 36, pp. 796-800, 1912.

[30] J. Algué, Mirador Observatory, Baguio, Benguet, 11 pp., Philippine Weath. Bur., Manila, 1909; base-stations at 1432 and 1455 m, intermediate station at 1497 m; observations published in reports of Weath. Bur., Manila.

[31] Climatological Data, and Bull. W, 2nd ed., U.S. Weath. Bur.; Hilo as base-station; the Weather Bureau has a number of rather high cooperating stations in Hawaiian Islands; observations of winds on Mauna Loa by Dutton, U.S. Geol. Surv., 4th Ann. Rep., 1884, p. 145.

[32] S. P. Fergusson, reference [12] and Appalachia, v. 12, pp. 146-153, 1918; see also article by him in this issue of Trans. Amer. Geophys. Union.

[33] Observations published in extenso in Misc. Pub. No. 6, p. 57, 1876, of the U.S. Geol. and Geog. Surveys of the Territories by F. V. Hayden.

[34] Observations reported in manuscripts to U.S. Naval Observatory; see E. S. Holden, reference [24].

[35] H. Draper, Amer. J. Sci., 3rd ser., v. 13, p. 89, 1877.

[36] A. L. Rotch, Amer. Met. J., v. 8, p. 404, 1892; these and the 1876 stations were run for short periods and equipped with simple self-recording instruments controlled by eye-observations.

[37] During August stations at Lone Pine 1158 m, Mountain Camp 3536 m, but at summit 4420 m from September 2 to 5 only; pressure, temperature, humidity, and weather observations; S. P. Langley, Nature, v. 26, p. 314, 1882; Prof. Papers, U.S. Signal Service, No. 15, 1884; Sci., v. 5, pp. 441-450, 1885; A. McAdie, Sierra Club Bull., v. 7, pp. 141-148, 1910.

[38] Elevations 1236 and 470 m, respectively, second-order stations; no base for Killington, but Bar Harbor for Green Mountain; monthly climatological summaries of observations in Mon. Weath. Rev. for next following months; some earlier observations made on Killington on file at Weather Bureau, Washington.

[39] Observations on file at Weather Bureau, Washington; Mansfield 1340 m; Bear Mountain 568 m, observations March, 1880, to November, 1882.

[40] Pressure, humidity, and temperature recorded continuously Aug. 28 to Sep. 4, the humidity-record being first continuous one obtained above 3000 m; observations briefly summarized by A. McAdie, Sierra Club. Bull., v.7, pp. 141-148, 1910, and more fully in Pub. Lick Obs., and by Smithsonian Inst.; McAdie discussed relative advantages of Mt. Whitney and other high peaks of Pacific Slope for meteorological observatories in Mon. Weath. Rev., v.33, pp.524-526, 1903, v.38, pp.1266-1270, 1910, and Sierra Club Bull., v. 6, pp. 7-14, v. 5, pp. 87-101.

[41] S. P. Fergusson, Appalachia, v. 12, pp. 146-153, 1918, and in reference [29]; data not yet fully analyzed.

[42] Reported by them in this issue of Trans. Amer. Geophys. Union.

[43] On summit for nine days in early August; observations include radiation, temperature, vapor-pressure, weather; A. Angström, A study of the radiation of the atmosphere, Washington, 1915; also discussed by N. Shaw, Manual of meteorology, v. 3, pp. 160-161, 200-201.

[44] See Ann. Astroph. Obs., and Ann. Rep. Smithsonian Inst.; Researches Dept. Terrestrial Magnetism, Carnegie Inst. Washington; Ann. Astr. Obs. Harvard College. The fine cloud-photographs of F. Ellerman at Mt. Wilson, California, have been widely published.

[45] The following stations not heretofore mentioned are suggested (for observations see Bull. W, 2nd ed., and Climatological Data, U.S. Weath. Bur.), others should probably be included (inquire of Weather Bureau for topographic situation of stations): Highlands and Rock House, North Carolina; Caesar's Head, South Carolina; Burkes Garden, Virginia; Crater Lake, Oregon; Paradise Inn, Washington; Mt. St. Helena, Tioga Mining District, Holcomb, Seven Oaks, Squirrel Inn, California; Fox Park, Wyoming; Bison Mountain, Montana; Breckenridge, Colorado; Pioche, Tybo, Belmont, Nevada; Frisco, Utah; Cloudcroft, New Mexico; Chlarson's Mill, St. Michaels, Pinedale, Tombstone, and Ft. Huachuca, Arizona.

[46] See Bibliography of meteorology--- to close of 1889, ed. by O. L. Fassig, U.S. Weath. Bur., 1891, 4 vols.; Indexes of Amer. J. Sci. ("Silliman's J."), J. Franklin Inst., Amer. Met. J., Appalachia, Sierra Club Bull., and other mountaineering journals, Bull. Amer. Met. Soc., Bull. Amer. Geog. Soc., Nat. Geog. Mag., Geog. Rev., and the card index of the Weather Bureau Library, Washington.

[47] See Biological (Botanical) Abstracts, indexes, and reviews in Ecology, J. of Ecology, and other botanical and forestry journals, and standard ecologic and phytogeographic treatises.

[48] Ann. Rep. Weath. Bur., v. 2, 1900-01.

[49] Mon. Weath. Rev. Suppl., No. 19, 1923; also J. W. Chickering, Amer. Met. J., v. 1, pp. 213-318, 1884-85, and L. T. Pierce, Mon. Weath. Rev., v. 62, pp. 8-12, 1934.

[50] Boston, 1925; in particular literature on chinooks, foehn mountain and valley breezes, and climatic effects of the various mountain ranges is well covered; note also R. J. Russell, Climates of California, U. Cal. Pub. Geog., v. 2, No. 4, pp. 73-84, 1926, and H. F. Morey, Climatological charts for Allegheny Forest Region, Mon. Weath. Rev., v. 59, pp. 18-28, 1931.

[51] Roderick Peattie, Les Apports de l'Amerique a la Climat. de Montagne, in Mélanges Géographiques offèrts à R. Blanchard, Univ. de Grenoble, L'Institut de Géog. Alpine, pp. 467-479, 1932.

[52] R. S. Monahan and S. Pagliuca, Trans. Amer. Geophys. Union, 14th annual meeting, 1933, pp. 85-88; R. S. Monahan, Mt. Washington reoccupied, Brattleboro, Vermont, 1933.
[53] S. Pagliuca, Mon. Weath. Rev., v. 62, pp. 16-18, 1934; S. Pagliuca and A. McKenzie, Manchester (New Hampshire) Union, Aug. 1, 1934, p. 1; W. M. McDonald, Boston Evening Transcript, pt. 4, Feature Sect., July 26, 1933; S. Pagliuca, three papers, Trans. Amer. Geophys. Union, this issue; S. P. Fergusson and I. I. Schell, articles in this issue Trans. Amer. Geophys. Union.
[54] S. Pagliuca and S. P. Fergusson, papers in this issue Trans. Amer. Geophys. Union; Rossby, Willett, Brooks, and others, Bull. Amer. Met. Soc., v. 15, 1934.
[55] Rossby, Willett, Brooks, and others, Bull. Amer. Met. Soc., v. 15, 1934.
[56] Geog. Rev., v. 19, pp. 150-151, 1929.
[57] P. Towle and E. M. Brooks, Bull. Amer. Met. Soc., v. 14, p. 116, 1933; this station and the Blue Hill Observatory also cooperated in the second Polar-Year program.

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ATMOSPHERIC IONIZATION NEAR GROUND DURING THUNDER-STORMS

G. R. Wait and A. G. McNish

(Abstract)

The rate of ionization inside a thin-walled vessel has been recorded on the grounds of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, during the past year. The rate of ionization was found to undergo an abnormal increase at the time of a thunder-storm. This increase has an abrupt beginning, coinciding with the beginning of the rain. The ionization decreases as soon as the rain ceases to fall. The curve which represents this decrease in ionization is substantially similar to the decay-curve for radium B. The increase in the rate of ionization, therefore, is attributed to radium B, and radium C in equilibrium with it, which must have been brought down by the rain, having become attached to the raindrops before they fell. It follows that large quantities of radioactive material must be present inside a thunder-cloud. The presence of such material can be fully accounted for on the assumption that vertical air-currents, which always occur during the formation of thunder-storms, carry it from the Earth's surface into the clouds. The presence of radioactive material in a thunder-cloud is of considerable significance in atmospheric electricity, especially in connection with theories as to origin of penetrating-radiation associated with thunder-storms, recently detected by Schonland, and in connection with the theory of the maintenance of the Earth's electric charge as put forward by C. T. R. Wilson. (For complete paper see Mon. Weath. Rev., v. 62, pp. 1-4, 1934.)

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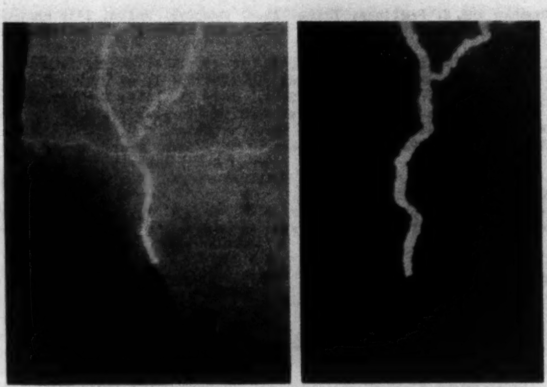
LIGHTNING-DISCHARGES TO GROUNDED CONDUCTORS

J. C. Jensen

There has recently been considerable discussion regarding the probability that lightning will strike a well-grounded conductor such as a lightning-rod, a metal smoke-stack, a steel transmission-tower, or a radio antenna. It is contended on the one hand that electricity escaping into the air from metal points such as are found on lightning-rods has a tendency to equalize the difference of potential between the clouds and the earth, and thus to decrease the danger of a lightning-stroke. This viewpoint is expressed by Professor J. B. Whitehead (Science, v. 78, p. 507, 1933), and is held by the majority of laymen. Dr. M. G. Lloyd (Science, v. 78, p. 603, 1933) and Dr. John Zeleny (Science, v. 79, p. 269, 1934) present evidence to show that thoroughly grounded conductors have been repeatedly struck and questioned the conclusions of Professor



Lightning-discharge to Empire State Building, New York, June 24, 1933
(From photographs, copyrighted 1933, by H. A. Shimer)

Whitehead regarding the 61 trees protected by metallic conductors and immune from lightning-strokes for seventeen years. After discussing these and other authorities, Dr. Hugh Skilling (Science, v. 79, p. 293, 1934) requests that more information be published regarding visible discharges from conductors during thunder-storms including the frequency of occurrence, the magnitude of the current, and related data. Subsequent to my recent publications (Physics, v. 4, p. 372, 1933, and J. Frank. Inst., v. 216, p. 707, 1933), much correspondence has come to my desk regarding phenomena of this kind, most of it being from competent observers.

Luminous discharges from trees, weather-cocks, and metal conductors on the roofs of buildings have been reported so frequently that their occurrence must be rather common. The writer has seen such visible discharges on only one or two occasions when they appeared on a highly insulated radio-transmitting antenna. This same aerial, suspended from a steel smokestack 100 feet high and supported by grounded guy-wires, has twice suffered direct hits. Large insulators between the antenna-wire and stack were blown to pieces and the wires completely fused, but, although the writer was in an adjoining building, it was impossible to determine whether the main bolt hit the antenna or the stack. Electrical engineers (see J. Frank. Inst., v. 216, p. 707, 1933) cite many instances of direct strokes to power-lines and transmission-towers, and similar data are contained in reports recently obtained from Dr. B. F. J. Schonland who has directed researches along this line in South Africa.

One of the best illustrations of heavy discharges to a thoroughly grounded conductor that has come to my attention was a series of direct hits to the mooring mast of the Empire State Building in New York on June 24, 1933. Five photographs were obtained within a few minutes by Henry A. Shimer with a small kodak, copies of two of which are shown above. It will be recalled that the Empire State Building is 1250 feet high, of structural steel framework all of which is thoroughly bonded and grounded. The outer structure of the tower is steel or aluminum, as is also the mast. This building may, therefore, be likened to a gigantic lightning-rod extending almost a fourth of a mile into the air. The pictures were obtained toward the close of a rather violent thunder-storm with low-hanging clouds. Considering the season of the year and the well-known high humidity in the vicinity of New York, it is probable that the lower portion of the cloud was less than a mile above the Earth. The effect of putting a well-grounded conductor up into the air a quarter of the distance to the cloud would be to increase the potential gradient between the two so that if a discharge should occur it would be almost certain to follow this path of least resistance. Attendants in the building report that when storms are close overhead the smell of ozone and the evidences of silent discharges are very noticeable. Other very unique pictures of lightning striking this same building have been reported by L. E. Gaty, who witnessed the bombardment recorded by Shimer a few days before (Illust. London News, Sep. 2, 1933, p. 357). Mr. Gaty's pictures were obtained with a high-grade lens and special red sensitive film, and show many striations and also have large, luminous, circular or oblong balls at their lower extremity next to the tower.

A marked peculiarity of Shimer's pictures is the fact that two of the five show upward branching at an altitude of approximately 1800 feet above the tower of the building, or 3000 feet above the Earth. This large percentage of discharges with the upward branches is the more significant in view of the fact that recent papers by E. C. Halliday (Phil. Mag., v. 15, p. 409, 1933), and B. F. J. Schonland and H. J. Collens (Proc. Roy. Soc., A, v. 143, p. 654, 1934) record only downward branching. The writer's own investigations (see J. Frank. Inst., v. 216, p. 707, 1933) showed only a total of eight photographs with upward branching out of 185. However, as previously mentioned, the pictures were obtained after the active portion of the storm had passed over and in rapid succession. They may, therefore, have come from the posterior portion of the cloud, corresponding to the part marked "negative rain" in Simpson's typical drawing of the cross-section of a thunder-cloud. The objection to this theory lies in the fact that so much concentration of electrical charges would not be expected in that part of the storm. Barographic records from the United States Weather Bureau at Battery Place, and from the Daily News office indicate that there was a secondary storm of considerable violence, following immediately after the first storm which began at 2:40 a.m. The secondary storm resulted in wind-velocities of 52 miles per hour with but little rain. From all the evidence now available, it is more probable that these discharges came from the front part of this secondary storm corresponding to the dense negative portion of Banerji's typical storm-clouds (Phil. Trans., A., v. 231, p. 1, 1932).

In conclusion, there is abundant evidence that lightning does repeatedly strike grounded conductors of all kinds, and also that visible discharges from trees as well as metallic conductors are rather frequent. In all probability, investigations now in progress will give definite information regarding the currents involved in lightning-strokes in the very near future.

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AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Washington, D. C.
April 26, 1934

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LISBON MEETING OF THE INTERNATIONAL ASSOCIATION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

J. A. Fleming

At the Fifth General Assembly of the International Union of Geodesy and Geophysics held at Lisbon, Portugal, September 14 to 23, 1933, there were five sessions of the Association of Terrestrial Magnetism and Electricity. The following countries were represented by delegates and guests: Denmark, Finland, France, Germany, Great Britain, Holland, Italy, Japan, Poland, Portugal, Spain, Sweden, Switzerland, and the United States.

The Association evinced its interest in many geophysical researches now in progress, among which may be mentioned: The continuous observation of solar phenomena which may lead to an explanation of the production of certain phenomena in the upper atmosphere, especially those for which magnetic observations have shown the origin to reside in more or less persistent areas on the Sun's surface; the results of spectroheliosсopic observations being obtained at stations widely distributed over the Earth's surface; the international aspects of cosmic-ray research, stressing particularly the desirability of furthering in every way the plans for installing and maintaining at selected permanent observatories apparatus for the continuous photographic registration of the penetrating-radiation; and observations relating to the form of lightning.

The reports of the Subcommittee on the Second Polar Year indicated highly satisfactory progress had been made and that a vast number of scientific data had been collected which would be of inestimable value in geophysical researches. The Association instructed its Executive Committee to contribute funds for the reduction of the results as liberally as the Association's budget may permit.

Questions pertaining to auroral observations engaged the attention of the Association, especially those pertaining to observations by amateurs and auroral catalogs. In the latter case, the Association emphasized the great service which would be rendered by directors of meteorological services were it arranged that their climatological stations make a matter of routine the recording of observed auroras, these records to be published annually in some suitable form. The importance of continuing the auroral program at College, Alaska, by the Alaska Agricultural College and School of Mines was emphasized.

The Association recorded its opinion that intercomparisons of national standards of coil-magnetometers should be carried out wherever and whenever possible, and indicated that this might be accomplished by indirect comparisons.

It was suggested also that a recalculation of the Gaussian constants of the Earth's magnetic field based on the latest data, particularly including the results of observations from the International Polar Year 1932-33, would be most desirable, and the Carnegie Institution of Washington was requested to complete the publication of the results of Bauer's analysis for the epoch 1922.

With the purpose of remedying as far as possible the present insufficiency and unsatisfactory distribution of magnetic and electric observatories over the Earth's surface, the Association gave careful consideration to the report of its Committee on the Selection of Sites for New Observatories for Magnetism and Electricity, which was approved. The Association adopted resolutions addressed to various governments emphasizing the value of existing observatory-work and of the great need for the establishment of additional stations as indicated by the Committee. The desirability was also expressed of obtaining, whenever opportunity affords, magnetic and electric observations for periods of not less than one year at polar stations in high latitudes, especially at Spitzbergen and at Little America.

Now that magnetic measurements have been made by most governments and in countries not having magnetic surveys and at sea largely through the expeditions sent out by the Carnegie Institution of Washington, at field-stations well distributed over the Earth's surface, the importance of obtaining repeat-observations at certain selected stations suitable for the study of the secular variation is apparent. A program for this work based on the exigencies of recent research and embodied in a report prepared by the Association's Special Committee on Secular Variation was adopted as a minimum requirement and the hope expressed that governments would take steps to secure secular-variation data not only within their own geographic limits but also in their colonies and mandated territories. It was deemed desirable also that funds be found for the construction and operation of a vessel similar to the Carnegie for continuing the magnetic and other geophysical work at sea unfortunately interrupted by the regrettable destruction of the non-magnetic vessel.

Many reports on current research and communications dealing with specific investigations in terrestrial magnetism and electricity were presented at the meetings. All these papers will be published in full or in abstract in the Transactions of the Lisbon Assembly which, it is expected, will be issued during 1934.

Committees were appointed on Resolutions; Statutes; Finance; Sudden Commencements; Aurora; Magnetic characterization; Relationships of solar activity and terrestrial magnetism; Polar Year; Selection of sites for new observatories, with a subcommittee on observatory work in Europe; Secular variation; Electrical characterization of days; and Editorial. The committees on terminology and on the relations with the International Meteorological Organization were discharged with thanks.

The following persons were designated to continue until the next assembly as reporters for the fields indicated: International cooperation to advance the study on effects of the Moon on geophysical phenomena, S. Chapman; magnetic numerical characterization of days, A. Crichton Mitchell; ion-counters, G. R. Wait.

The new officers of the Association unanimously elected for the period through the next assembly in 1936 at Edinburgh, Scotland, are as follows: President, J. A. Fleming; vice-presidents, V. Carlheim-Gyllensköld and Ch. Maurain; secretary and director of the Central Bureau, D. la Cour; additional members of the Executive Committee, J. Agostinho, S. Chapman, A. Crichton-Mitchell, C. Störmer, and A. Tanakadate.

For greater deails of the proceedings of the Association at the Lisbon Assembly, and the complete text of the 23 resolutions adopted, reference may be made to the published report by J. A. Fleming and H. D. Harradon entitled "Fifth General Assembly of the Association of Terrestrial Magnetism and Electricity at Lisbon, Portugal, September 14 to 23, 1933" (Terr. Mag., v. 38, pp. 313-322, 1933).

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THE STUDY OF ATMOSPHERIC ELECTRICITY IN SOUTH AFRICA

B. F. J. Schonland

Atmospheric electricity presents many problems requiring world-wide cooperation. The values and variations of the atmospheric potential-gradient, the air-earth current, the factors controlling ionization-equilibrium in the lower air, the intensity of the cosmic radiation, the conductivity of the upper air, and the disturbed fields produced by thunder-storms and other agencies must all be carefully and continuously observed in all possible parts of the world if the problems they offer are to be effectively solved.

At the present time the investigation of every one of these factors in the electrical state of the atmosphere seems to be entering upon a new and fruitful phase. Fresh methods of attack are being developed, the relative importance of each variable is much clearer than before, and more facilities are being provided for world-wide and continuous observation. It is hoped that much of this new material may come from the African Continent.

Africa is of special interest in this study because it is a very important contributor to the world's supply of thunder-storms. Recent investigations by C. T. R. Wilson and others have made it seem probable that the thunder-storm is closely linked with many of the problems of atmospheric electricity. Some of these are the maintenance of the fine weather field, the creation of anomalous conducting-layers in the upper air, the production of penetrating-radiation, and of atmospherics.

There is at the present time evidence of much interest in the subject in South Africa. Investigations upon the electric moments, charges, and polarity of thunder-clouds have been carried out for the past eight years and are being continued. The interchange of electricity between the Earth and the atmosphere by point-discharge has been studied (Schonland), and a series of investigations has succeeded in establishing the existence of a penetrating electron-spray emitted by thunder-clouds (Schonland, Viljoen, and Malan).

Continuous observation of the atmospheric potential-gradient has been made at Johannesburg. A station continuously recording the intensity of the cosmic radiation has been operating for over a year as one unit in the international scheme organized by Steinke, Hess, Kohlhorster, and others (Schonland, Delatizky). Many of these investigations have been possible only through the generous financial support of the Carnegie Corporation of New York acting through the South African Research Grant Board.

The further study of problems of thunder-cloud has recently received considerable impetus from a very welcome source. The South African Institute of Electrical Engineers decided in 1932 to form various committees to investigate problems connected with lightning. One of these committees is educational, another statistical, and the third, of which the author is chairman, is concerned with research. The Institute has collected funds for the support of these investigations from various municipalities, corporations, and scientific societies. The scientific research program of the Institute has only been in operation for one year. Its activities have been restricted to three main lines.

The first and most extensive of these is the study of the mode of development of the lightning-discharge. For this investigation use has been made of the rotating-lens camera developed by C. V. Boys and previously operated with some success in South Africa by Halliday. These cameras have been constructed locally and with certain modifications suggested by experience. Four of them are now in the field, one in the North Transvaal, two in Johannesburg, and one in Durban.

Very successful results have been obtained with this instrument by H. A. Collens, some of which have already been reported on (B. F. J. Schonland and H. Collens, Progressive lightning, Proc. R. Soc., A, v. 143, pp. 654-674, 1934). Photographs have been obtained of 75 lightning-flashes, comprising 141 separate strokes, and it is the intention to continue this work for some time. The Committee has under consideration the question of daylight investigation of lightning using a quartz-fluorite combination and an ultraviolet-filter. These studies of the development of the lightning-discharge have an additional importance in the light they shed upon the difficult question of the inception of the electric spark.

The second line of investigation concerns the production of penetrating rays by thunder-storms, including the possible existence of a penetrating-radiation at the point where a lightning-flash strikes the ground. With this object there have been installed suitable detectors of the radiation on the poles of a power-line frequently struck by lightning. Other methods of investigating this problem are also being used.

Point-discharge, the third line of investigation, is being studied by Mr. Immelman at the University of Pretoria. Water micro-voltammeters of the Wormell type have been constructed and two stations have been set up for continuous registration of the quantities of electricity interchanged via a projecting point between the Earth and the air. It is hoped to have eventually a chain of such stations throughout the continent.

An investigation is also in progress to determine whether there is any anomalous conductivity of the atmosphere at the neighborhood of points frequently struck by lightning.

It is hoped later to extend the work of the Committee to other problems afforded by the thunder-storm. The study of atmospherics, of the nature of lightning-surges along transmission-lines, and of various botanical and geological features of the places struck by lightning are some of these.

There are one or two features of these developments in research in atmospheric electricity in South Africa which may be briefly mentioned. This forward movement has been considerably accelerated by the powerful support of a body of practical engineers, who feel that basic scientific investigation into problems of lightning will be of value to them. For the same reason we are fortunate in having the interest and support of the largest power-company in the British Empire, which supplies the Johannesburg mines. The personnel involved, numbering some ten or twelve investigators, consists of lecturers from four different universities together with private individuals, several electrical engineers, and one farmer, all of whom are taking part in their spare time. In this way we have been able to operate with the advantage of the workshop and instrumental equipment from four different university institutions. Our chief expenditure has been on material for the construction and operation of the instruments employed.

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ATMOSPHERIC-ELECTRIC OBSERVATIONS AT THE COLLEGE-FAIRBANKS POLAR-YEAR STATION

K. L. Sherman

There is a very great lack of extended series of observations of the electrical elements of the lower atmosphere in the northern latitudes and particularly is this true of those regions to the north of our own Continent. Several expeditions into the Arctic have made measurements of the atmospheric potential-gradient, but very few measurements of such elements as air-conductivity or ionic content have even been attempted. The interval of the International Polar Year of 1932-33 was recognized as a very desirable time to obtain additional observations in the field of atmospheric electricity, from both administrative and scientific viewpoints. Simultaneous observations of meteorological and other related phenomena would be obtained and would be available later for study toward the end of determining those factors influencing the electrical state of the atmosphere and of course in finally fitting all the factors together in a complete picture. So it was that a comprehensive observational program in atmospheric electricity was planned for the College-Fairbanks Polar-Year Station to be carried out at College, Alaska.

The location at College proved to be very suitable for making these observations. With but few minor departures, occasioned mainly by difficulties encountered due to the extremely low temperatures, the program was carried out as planned. It consisted of obtaining continuous records of the atmospheric potential-gradient, of the conductivity due to both positive and negative ions, and of eye-observations once daily of the number of positive and negative small ions and of Aitken nuclei. Out of the eleven-month period from October 1, 1932 to September 1, 1933, during which observations were made, complete daily registrations were obtained on 85 per cent of the total number of days for each of the three recorded elements; on only 15 per cent of the days were records for whole days or fractions of days lost due either to instrumental difficulties or to disturbing electrical conditions. As an indication of the freedom from disturbing local conditions, of the 85 per cent of complete days of registration of atmospheric potential-gradient 75 per cent were free from negative potentials and therefore were eligible for further consideration as representative days. The small amount of winds found at College during the winter lessened considerably uncertainty in the potential-gradient results due to frictional charges generated by the moving snow-particles or to a changing collector-position relative to the zero reference-point arising from snow-drifts. The main source of instrumental difficulty was the forming of frost over parts of the apparatus, which can be very troublesome when making electrostatic measurements, since excellent insulation must be maintained.

To obtain the atmospheric potential-gradient, the potential at a point at the variation-observatory was recorded. In order to reduce these values to the accepted standard of volts per meter over a plane area, a standardizing observatory was operated about one-half mile distant, where the electrical field was little altered by natural or artificial disturbing-influences. This second station was operated nearly continuously, so that considerable data in excess of those considered needed for adequate control were obtained, providing as well additional data for special studies. At both stations a small disc coated with radioactive material was used as the "collector." This "collector" was connected to the insulated system of an electrometer which recorded the difference of potential between the "collector" and earth. Two different types of electrometer were used for the recording, a Benndorf quadrant-type at the variation-observatory and a Günther and Tegetmeyer bifilar at the standardizing observatory.

The electrical conductivity was measured using a modification of the Gerdien aspirator. The modified apparatus was a semi-portable type similar to that developed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for use on board the Carnegie. Air drawn through a 6-inch earthed tube passes a 3/4-inch cylindrical rod mounted centrally in the tube. The rod is maintained at a potential whose sign is governed by the sign of the conductivity to be measured. Some of the ions in the air having opposite sign to that of the rod are attracted to the rod as the air passes. The charge as it is gathered by the rod is permitted to leak off to earth through a resistance of about 10^{12} ohms. The ir-drop produced by the current as it flows through the resistor is recorded by a single-fiber electrometer. The magnitude of the current during registration may be determined by comparing the deflection caused by it with the deflection produced by a known current sent through the resistor at time of calibration. Knowing the current and instrumental constants, the conductivity may be computed.

For making the observations of ionic content, an improved type of Ebert counter was used. Among other improvements, a single-fiber electrometer was used instead of a bifilar instrument.

Much work still remains to be done on the computation and analysis of the observations obtained; however, sufficient progress has been made from which to draw some preliminary conclusions. No startling anomalies are found on comparing these records with those obtained from stations elsewhere. The potential-gradient diurnal-variation curves show very markedly the universal 24-hour wave-component, which reaches its maximum everywhere at about 18^h Greenwich time and which was pointed out by Mauchly from his analysis of the data secured aboard the Carnegie. The average yearly value is quite normal, being very closely 100 volts per meter. A monthly maximum occurred in January and a minimum in August, quite consistent with land-stations farther south but differing from a maximum in April as found by Sverdrup in the arctic.

In judging the conductivity-data obtained here, we have no rigid criterion to which it must conform to be considered as representing a normal condition. Such criteria as we do have, however, indicate that the values obtained are quite what would be expected. An average total conductivity of approximately 3×10^{-4} e.s.u., with the positive about one and one-third times the negative, agrees closely with other observations. The diurnal curves are characterized, particularly in winter, by a double maximum--a typical early-morning maximum at about 4 o'clock and an afternoon maximum at about 6 o'clock. In summer, the daily amplitude was considerably decreased, and in this respect is opposite to that found at Washington where the diurnal range increases in summer. The annual curve by months shows a maximum in October, a confirmation of other results which have indicated, with increased latitude, a shift of the maximum from winter toward autumn.

The ionic-content observations have only been computed for the month of November, when the number of positive ions ranged from 500 to 1700 and the negative from 300 to 1000 ions per cubic centimeter.

No exhaustive comparison has been made looking toward a correlation between the electric condition of the lower atmosphere and that of the upper air as evidenced by auroral displays. It can be said that there is no outstanding relation between the aurora and air-conductivity. As for atmospheric potential-gradient, these results will corroborate the findings of Sverdrup in showing no simultaneous pulses in the gradient with those in aurora, but they do indicate a depression in the potential gradient following auroral displays.

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RECENT RESEARCHES ON FLUCTUATIONS OF COSMIC-RAY IONIZATION

James W. Broxon

This communication summarizes briefly the most recent researches and publications, more particularly during 1932-33, bearing on fluctuations of cosmic-ray ionization. It appears that the findings of the last year have already provided rather convincing evidence for the existence of influences upon the cosmic radiation due to water-content of the atmosphere and to terrestrial-magnetic disturbances. Classification of these may be expected to be provided by long-continued, continuous observations, and through cooperation of observers on a world-wide basis.

This paper, read by title in the absence of the author at the meeting of the Section of Terrestrial Magnetism and Electricity, is printed in full in the June 1934 number of the Journal of Terrestrial Magnetism and Atmospheric Electricity.

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STUDIES OF THE CORPUSCULAR COMPONENT OF THE COSMIC RADIATION

Thomas H. Johnson

Evidence of the corpuscular nature of the primary cosmic radiation is found both in the geographical and in the angular distribution of its intensity. In his study of auroral phenomena Störmer (Zs. Astrophysik, v. 1, p. 237, 1930) obtained a solution for the orbits of charged particles projected from outside into the magnetic field of the Earth and he, as well as Rossi (Nuovo Cimento, v. 8, No. 3, pp. 3-15, 1931), have pointed out the application of this solution to the distribution of the cosmic-ray intensity. Störmer's equation shows that for rays of electronic mass and of a particular energy, unless this be above 10^{10} volts, there is an inaccessible equatorial zone on the surface of the Earth into which no ray can enter regardless of its initial position and direction. On either side of the inaccessible zone are zones only partially accessible to rays of the energy in question since here these rays may reach the Earth's surface only on orbits which lie within a cone of limited aperture. At the edge of the inaccessible zone this cone opens up with infinitesimal aperture in the direction of the western horizon for positive rays and towards the eastern horizon for negative rays, but as the point of observation is moved to higher latitudes the cone of possible orbits opens up continuously and eventually fills the entire sky. As an example, the surface of the Earth at the equator is completely inaccessible to rays of energy less than 10^{10} volts and is completely accessible only to rays of energy greater than 6×10^{10} volts. The 45° parallels, on the other hand, begin to be accessible to rays of energy 3.3×10^9 and are completely accessible to rays of energy greater than 4.9×10^9 volts.

Assuming the presence of electrically-charged particles in the primary radiation, the theory thus predicts the lower equatorial intensity found by Clay and Compton, and, if one sign of charge predominates, the theory also predicts the directional asymmetry. The finding of both of these effects, therefore, may be regarded as proof of the existence of the corpuscular component.

As to the asymmetry, our Mount Washington experiments (T. H. Johnson and J. C. Street, Phys. Rev., v. 43, p. 381, 1933) in 1932 had shown a slightly greater intensity from the west than from the east at the same zenith-angles, indicating a positive primary component and, since latitude intensity-variations had then been found in equatorial regions, it was evident that greater asymmetries would also exist there if the corpuscular hypothesis were tenable. With the support of the Cosmic-Ray Committee of the Carnegie Institution of Washington and with financial aid from the Carnegie Corporation of New York and the Bartol Research Foundation of The Franklin Institute, a survey was undertaken during the spring and summer of 1933 to measure the directional effects in the equatorial belt. The stations at various elevations above sea-level and at which observations were made include three on the magnetic equator in Peru, one at geomagnetic latitude 20° in the Panama Canal Zone, and three at geomagnetic latitude 29° in Mexico; Stevenson, as a part of the same general program,

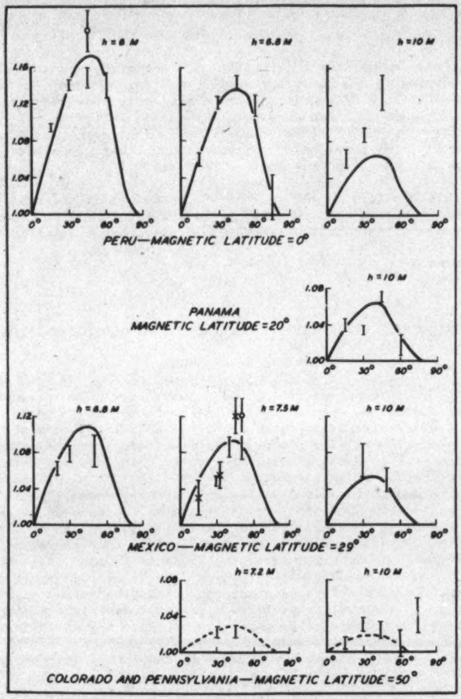

FIG. 1—INTENSITY—RATIOS (J_W/J_E) VERSUS ZENITH-ANGLE AT VARIOUS LOCATIONS

made measurements at geomagnetic latitudes 50° in Colorado and in Pennsylvania. Other independent measurements have been made giving results also in agreement with our own. Of these particular mention is made of the results (see crosses in Fig. 1) of Alvarez and Compton (L. Alvarez and A. H. Compton, Phys. Rev., v. 43, p. 835, 1933).

The results obtained are shown graphically in Figure 1, where ratios of western to eastern intensities are plotted for each location as functions of zenith-angle. The probable error of each ratio has been determined from the actual spread of the data which, in most instances, include over 100 independent determinations, and these are represented by the vertical lines. The smoothed curves represent an empirical equation involving the energy-limits given by the theory and containing an intensity-factor and an absorption-factor.

The results bring into evidence the following facts: (1) The asymmetry is greatest at the equator; (2) the percentage-asymmetry increases with elevation; (3) the percentage-asymmetry is maximum at intermediate zenith-angles probably vanishing at the horizon; and (4) the data obtained with a lead absorbing-screen 3.8 cm thick and represented by the circles of Figure 1 indicate, but are not sufficiently accurate to prove, that the percentage-asymmetry is greater if the soft secondary rays are cut out, thus indicating that these may be slightly diffused with respect to their primary directions. The nature of the variation of the asymmetry with elevation and zenith-angle shows the asymmetrical radiation to be softer than the average. The variation with latitude, on the other hand, is such as to rule out the possibility that the asymmetry could be produced as a consequence of the action of the Earth's magnetic field on charged secondary particles produced in the atmosphere itself. The asymmetry is therefore produced by the action of the field on rays which are definitely primary, positively-charged particles.

From a consideration of the magnitude of the asymmetry in relation to the magnitude of the latitude intensity-variations it is possible to estimate the relative intensities of the positive and negative components. This is possible because the latitude intensity-variations are produced by the sum of positive and negative components whereas the asymmetry is a differential effect produced by the excess of positive over negative intensity. Lemaitre and Vallarta (G. Lemaitre and M. S. Vallarta, Phys. Rev., v. 43, p. 87, 1933, and M. S. Vallarta, Phys. Rev., v. 44, p. 1, 1933) have given the limiting energies for cones of various angles at various latitudes and the values corresponding to equal angles on each side of the meridian define the band of energies which produce the east-west asymmetry at that angle. The magnitude of the asymmetry is therefore a measure of the excess of positive over negative intensity throughout that energy-band.

Similarly the difference between the intensities from a particular direction but at different latitudes is a measure of the sum of the positive and negative components in a band of energies extending from the limiting value for the one latitude to that for the other and for that particular direction. The two results may therefore be combined to give values of the positive and negative intensities separately. Using the asymmetry-measurements together with the latitude intensity-measurements of Auger and Leprince-Ringuet, made with a train of counters pointing in the vertical direction, it is found that within the rather wide limits of experimental accuracy the radiation is entirely positive. The more accurate measurements of the latitude-effect made with electroscopes may also be introduced into these calculations, but in this case it is necessary to first assume a definite proportion of positives and negatives, the intensities of which may then be determined from the asymmetry. The result is used then to calculate the latitude-effect at each angle and this is averaged over all angles for comparison with the measured latitude-effects. In Table 1 are given values of the averaged latitude-effects, calculated on the assumption that the corpuscular radiation is entirely positive, and they are to be compared with the values observed (compare also T. H. Johnson, Phys. Rev., v. 45, pp. 569-585, 1934). The agreement is as good as could be expected in view of the rather wide range of observed values and it is concluded that within present accuracies the positive component is sufficient to account for the entire latitude-effect. A consideration of

Table 1--Comparison of observed latitude intensity-variation (expressed as percentage-increases over the value at the equator) with values calculated from asymmetry, assuming an exclusively positive, corpuscular component

Latitude	Depth of water	Calculated	Observed			
			Compton	Bowen, Millikan, and Neher	Clay	Hoerlin
°	m					
20	10	1	1	0	2	0
	6	3	3	0	..	..
29	10	3	4	..	6	2
	6	7	10	..	..	..
50	10	9	14	7	15	10
	6	23	33	25	..	..

possible sources of error conservatively places the upper limit of the negative radiation at less than 17 per cent of the positive.

Having determined the intensity per unit energy-range from the asymmetry it now becomes possible, by integration between the extreme limits of energy which come within the range of observation, to determine a lower limit for the intensity of the positive component at high latitudes where no part is excluded by the magnetic field. In this way it is found that at least 13 per cent of the total intensity at sea-level and 33 per cent at 14,000 feet above sea-level is due to positives. Considering the vertical intensity alone at least 58 per cent at 14,000 feet above sea-level can be accounted for in the same way. With the possibility of still wider ranges of energy than those which come into the range of the asymmetry-observations it is evident that a very large part of the total intensity can be attributed to these positive primaries. In fact, the only component revealed by the absorption-curve analysis, which is large enough to contain the corpuscular radiation, is the intense soft component which all observers agree contains more than 90 per cent of the total incident-radiation and accounts for 65 per cent of the intensity at 14,000 feet above sea-level.

That this component does actually consist of the positive corpuscular rays is further supported by the agreement of the absorption-coefficient of the positive component with that of this band as derived from the absorption-curve. Although the asymmetry-measurements, as represented in Figure 1, and expressed as the ratio of east-to-west intensity, depend only upon the difference between the coefficients of the corpuscular and average radiations, the true coefficient may be derived by combining this difference with the effective coefficient for the total radiation at the same elevations as determined either from the zenith-angle distribution or from the ionization-depth curve. In this way the absorption-coefficient for the asymmetrical radiation is found to be nearly independent of latitude and equal to 0.52 per meter of water. This value has the experimental support of (a) the variation of asymmetry with zenith-angle, (b) the variation of asymmetry with elevation, and (c) the variation of latitude-effect with elevation. For the coefficient of the intense soft component, on the other hand, the values given respectively by Bowen, Millikan, and Neher, and by Kramers and Rigener are 0.55 and 0.518. The agreement of these values with that obtained for the positive component is striking and, combined with the above considerations of intensity, constitutes a valid reason for identifying the positives with the soft component. The remaining intensity, not accounted for by positives in the observable energy-range, is also probably due to similar rays of higher energy.

The magnetic energy-determinations give now, for the first time, the opportunity of studying the absorption in the atmosphere of rays of known energy; and the results are radically different from what would have been expected on the basis of almost any hypothesis as to the mass and charge of the primary rays. Positrons of energy 1.5×10^{10} volts, corresponding to the mean energy of the asymmetrical bands at the equator, according to existing ideas, would have been expected to penetrate 55 meters of water, and the corresponding absorption-coefficient would have been 25 times smaller than that observed. The expected behavior of protons or deutons would not be radically different. The assumption of alpha-particles, or heavier nuclear particles, as the primary rays would explain the high observed absorption-coefficient, but this hypothesis would not account for the invariance of the coefficient with latitude. For any type of radiation this would have been expected to undergo a variation of a factor of ten for energies corresponding to the asymmetrical bands at the equator and at latitude 50°, yet the shape of the asymmetry versus zenith-angle curves of Figure 1 shows that no appreciable change in this coefficient has taken place. The fact that latitude intensity-variations cease at latitude 50° corresponding to an energy of 2.5×10^9 volts shows the existence of a sudden increase of coefficient, or a sudden drop in intensity for this energy, but the shape of the asymmetry curves of Figure 1 shows no appreciable change in this coefficient from this energy on up to an energy ten times greater.

Before the explanation of this situation can be given, further and more precise measurements of the asymmetry will be required in intermediate latitudes between latitudes 50° and 30°. At the present time the most hopeful interpretation would seem to be that the primaries are protons but that they lose energy much more rapidly than would have been expected on the basis of the theory of ionization. The fault of this theory may be its failure to take account of the little understood process of shower-production. In fact, measurements of the coefficient of absorption of the shower-producing component made both by changes of elevation and from the barometer-effect for three counters in triangular arrangement, covered by one cm of lead, also give a value close to 0.5. This shows that showers are produced by the positive rays and that their production may be one of the principal processes of energy-loss. The fact that the coefficient of absorption is 0.5 per meter of water indicates that the absorption is due principally to nuclear collisions since this is just the coefficient to be expected if absorption depends upon the probability of colliding with an entity of the size which experiments have shown the nucleus to possess, that is, about 2×10^{-13} cm.

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RADIO AND EARTH-POTENTIAL OBSERVATIONS IN NEW ENGLAND

G. W. Kenrick and P. M. Goldberg

In a paper previously presented to this Section some of the apparatus for field-intensity observations now in progress at Tufts College in Medford, Massachusetts, was described (G. W. Kenrick and G. W. Pickard, Recent developments in radio transmission-measurements, Trans. Amer. Geophys. Union, twelfth annual meeting, 1931, pp. 101-108). Statistical studies utilizing some of these data have also been discussed (G. W. Kenrick and G. W. Pickard, Some common periodicities in radio transmission-phenomena, Trans. Amer. Geophys. Union, thirteenth annual meeting, 1932, pp. 172-179). During the past year this work has continued and has been supplemented by related studies of earth-potentials and by continuous records of the effective height of the Kennelly-Heaviside layer.

The series now in progress at Tufts include:

(1) Observations of field-intensity in the broadcast-band (Boston-Chicago WBBM series 1926 to April 1934).
(2) Observations of low-frequency field-intensity. This represents a continuation of low-frequency observations similar to those initiated by Austin in 1912 and overlapping his series, which was discontinued at Washington in 1933 (Boston series from 1928 to April 1934 on WCI, and 1932 to April 1934 on European stations).
(3) Observations of radio transmission on six megacycles. These observations have continued through three years--1931 to April 1934--but have been on various stations due to changes in frequency-allocations in the stations originally chosen.
(4) Observations of earth-potential variations in New England. This series of observations was undertaken in collaboration with the New England Telephone Company as part of the studies of earth-potential observations throughout the United States during the Polar Year. Data are available from late 1931 to April 1934.
(5) Observations of the effective height of the Kennelly-Heaviside layer. This series includes observations of the effective height of the Kennelly-Heaviside layer at Boston, extending over a period from late in 1932 to April 1934.

The development of apparatus and of some of the statistical studies associated with the above projects (1), (2), and (3) are the subject of several published papers (De Mars, Kenrick, and Pickard, Low-frequency radio transmission, Proc. I. R. E., v. 18, pp. 1488-1501, 1930; De Mars, Kenrick, and Pickard, Use of automatic equipment in radio transmission-research, Proc. I. R. E., v. 19, pp. 1618-1633, 1931; and Kenrick and Pickard, Phase-interference phenomena in low-frequency radio transmission, Proc. I. R. E., v. 22, pp. 344-358, 1934).

Further statistical studies relating to these projects and utilizing the data accumulated since the publication of the papers cited are contemplated and, in some cases, are already in progress. Space does not permit a detailed discussion of these investigations in this report, although it is perhaps of interest to note that in nearly every case additional long-time trends apparently closely associated with the 11-year sunspot-cycle can be noted. It is hoped that in forthcoming publications at least some of the data available may be made accessible in the form of tables which can be used by other investigators. The effective presentation of this material in concise form is, however, in itself no little problem, since the available data are in

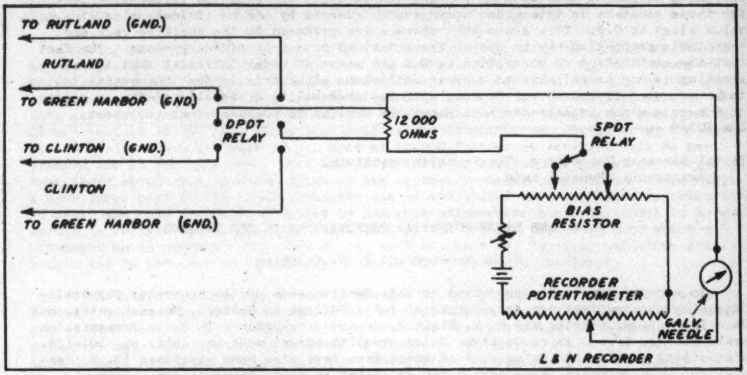
TO RUTLAND (GND.)
RUTLAND
TO GREEN HARBOR (GND.)
DPDT RELAY
12 000 OHMS
SPDT RELAY
TO CLINTON (GND.)
CLINTON
TO GREEN HARBOR (GND.)
BIAS RESISTOR
RECORDER POTENTIOMETER
GALV. NEEDLE
L & N RECORDER

Fig. 1--Schematic diagram of earth-potential recorder-circuit (switches are automatically shifted every two minutes)

most cases in the form of continuous records which are far too voluminous to permit their complete publication or general distribution. In such a situation the parameters which should be tabulated, of course, depend on the character of the investigation in which the data are to be utilized. This difficulty has long been appreciated in the case of magnetic records, but a characterization similar to the generally-adopted convention of a zero-, one-, and two-rating by magneticians seems by no means the ideal solution, and is far from eliminating personal equations. The work of reduction of the data derived as a result of the varied projects outlined above has presented many problems of this sort, since the phenomena are so varied that no significant uniform and quantitative index, which can be applied to all the types of data available, has been found thus far.

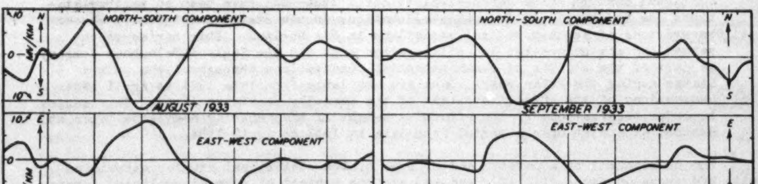

Fig. 3--Plot of typical monthly means for 1933, showing diurnal changes and their seasonal characteristics

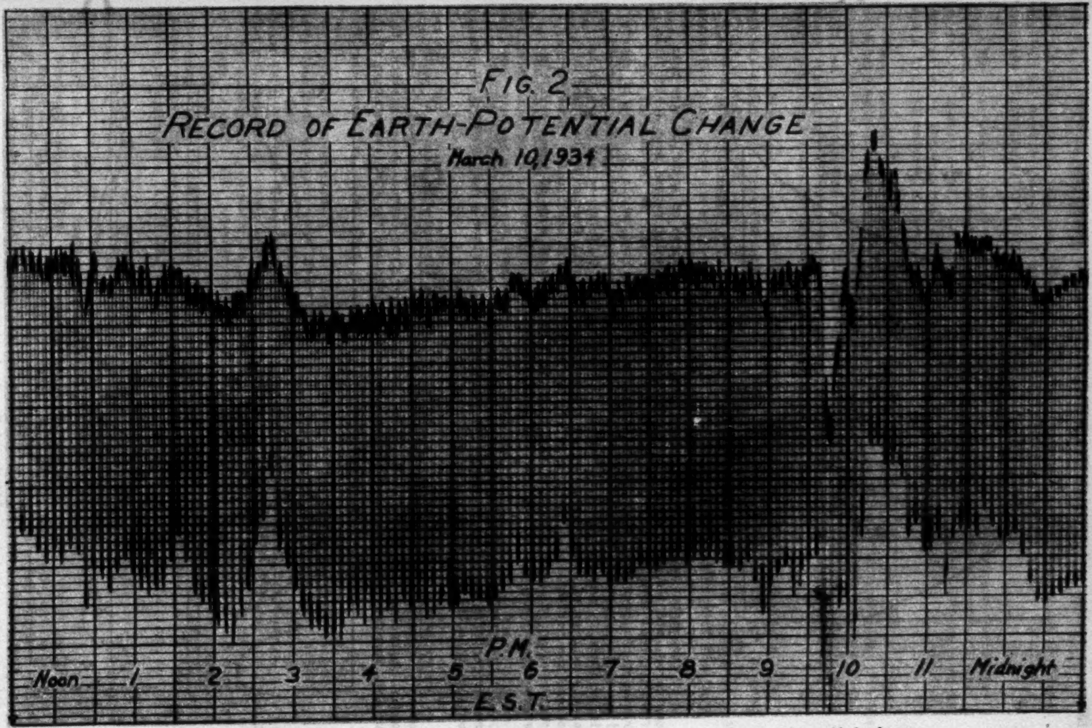

Fig. 2--Typical record obtained from earth-potential recorder, showing two minor disturbances

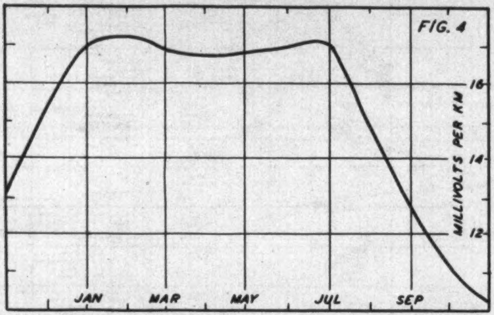

Fig. 4--Monthly maximum amplitude of diurnal earth-potential changes showing variation in amplitude, Boston, 1933

In the reduction of the series of data, various measures of activity have been considered, and the ones chosen have been usually those which proved most susceptible of statistical investigation in the studies already reported. In the case of the broadcast-observations, mean field-intensities were utilized, while in cases of short-distance low-frequency transmission from an American station a ratio of day-to-night field-intensity seems more significant. However, these differences may prove to be largely matters of convenience, since several measures will frequently be found to possess the periodicities to be studied, but with different amplitudes. Some further consideration of these questions and a comparative study of some of these possible measures seems appropriate before the publication of such data.

In the remaining sections of this paper we propose to discuss results derived from projects (4) and (5) listed above which have not previously been covered in reports to this Section.

Observations of earth-potential variations in New England--The series of earth-potential observations comprises observations over two circuits--one extending from Boston, Massachusetts, to Clinton, Maine, and the other from Boston, Massachusetts, to Rutland, Vermont. The wire-facilities were provided through the kind cooperation of

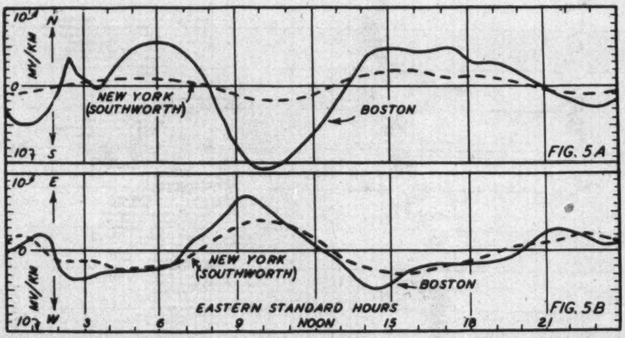

Fig. 5--Comparison of New England and New York (Southworth) data for October 1933, showing greater amplitude of New England data, particularly in north-south direction the New England Telephone and Telegraph Company. In August 1933 the ground at Boston was shifted from Boston proper to Green Harbor, Massachusetts, to reduce local extraneous disturbances to a minimum.

The observations were recorded with the aid of a Leeds and Northrup recording-galvanometer, which was connected alternately to the terminals of each circuit for periods of approximately two minutes. A modification of origin-bias permits a ready separation of the records. A schematic diagram of the circuit is shown in Figure 1 and a typical record is shown in Figure 2.

Data reduced from observations utilizing this equipment are available from 1932 to date. As a check on the validity of the data thus obtained, monthly curves for the diurnal period have been investigated for the period from November 1932 to December 1933, which includes most of the Polar Year of 1932-33. Copies of some results from these records are shown in Figure 3. Marked evidence of a periodic trend in the monthly diurnal characteristics is indicated.

The maximum amplitude of this periodicity by months is shown in Figure 4. It will be noted from Figure 5 that in October 1933 the New England results are in good accord with those published by Southworth, but the amplitude of the variation is greater than that obtained from Southworth's New York observations by a factor of about twofold. This is believed to be due to the high earth-resistivity in New England. The difference is particularly notable in the north-south values. It is interesting to note that the dominant direction of the earth-current disturbances shifts periodically from the east-west to the north-south loop.

Magnetic effects in low-frequency radio transmission--The availability of earth-potential records at the point of observation of low-frequency field-intensities has facilitated a study of short-time as well as long-time correlations between magnetic activity (or more strictly, earth-potentials) and low-frequency transmission.

The correlation between the ratio of average-night to average-day signal-intensity with magnetic periodicities for Station WCI located in Tuckerton, New Jersey, and received at Boston, Massachusetts, has already been discussed, together with certain other periodicities in radio transmission (see reference above in Trans. Amer. Geophys. Union, thirteenth annual meeting, 1932, pp. 172-179, and in Proc. I. R. E., v. 18, pp. 1488-1501, 1930, respectively; it is interesting to note that the 32-day period shown prominently in many phasograms presented in the first reference corresponds closely with the period of rotation of the Sun's magnetic poles). These periods have also been shown to exist in the low-frequency trans-Atlantic series at 10 a.m. The relation of the values at 10 a.m. to magnetic storms has also been pointed out (I. J. Wymore, The relation of radio propagation to disturbances in terrestrial magnetism, Proc. I. R. E., v. 17, pp. 1206-1213, 1929).

Recent observations of low-frequency field-intensities from European stations have disclosed several cases of an apparent short-time correlation between earth-potential changes and rapid field-intensity changes from low-frequency European stations (see Fig. 6). Such changes by no means invariably accompany the earth-potential changes, but enough cases are noted at two points of observation to render the reality of the phenomenon probable. A more extended statistical study extending over a period of years is desirable, however, before positive conclusions may be drawn. A more detailed discussion of this phenomenon is contained in the related paper entitled "Low-frequency radio transmission over trans-Atlantic paths" by Beverage and Kenrick presented before the meeting of the American Section of the International Scientific Radio Union at Washington, April 27, 1934.

Observations of the effective height of the Kennelly-Heaviside layer--Since November 1932 observations of the effective height of the Kennelly-Heaviside layer have been made at Boston, Massachusetts, utilizing equipment constructed with the aid of grants from the Rumford Fund and maintained and operated with the aid of grants from the Permanent Science Fund. This apparatus is an extension of that described in the paper entitled "Observations of the effective height of the Kennelly-Heaviside layer and field-intensity during the solar eclipse of August 31, 1932" (Kenrick and Pickard, Proc. I. R. E., v. 21, pp. 546-566, 1933). The observations have included frequencies of 2050 kc, 2398 kc, 3492 kc, and 4095 kc. A comparison of these observations with

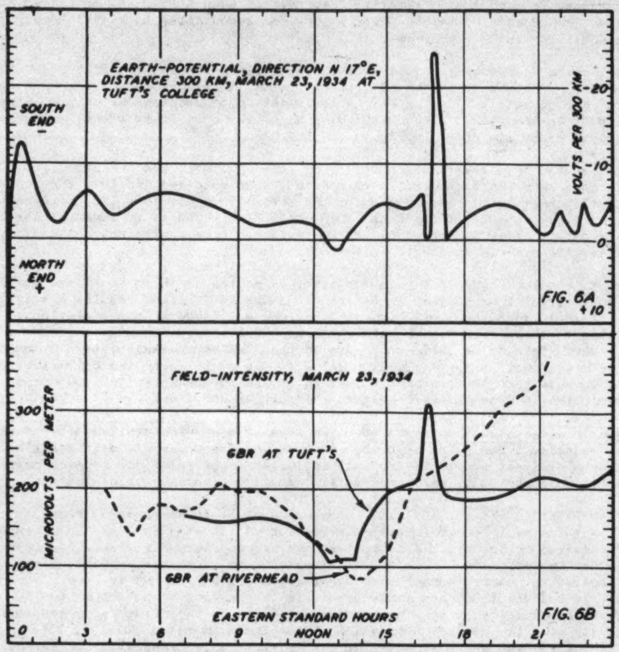

Fig. 6--Plots of earth-current and of field-intensity variations, March 23, 1934 (Note correlation between rapid change in signal-intensity at Boston and change of Boston magnetic field)

published results for Washington, D. C., shows marked evidence of a lower electron-density at Boston, Massachusetts, than at Washington, D. C., particularly during the evening hours (Kirby, Berkner, and Stuart, Studies of the ionosphere, Proc. I. R. E., v. 22, pp. 481-521, 1934).

Thus, referring to Figures 7, 8, 9, and 10, it will be noted the characteristic of diurnal height-variation at Boston shows much earlier cut-off times--that is, times of disappearance of the layer--at Boston than are shown for the corresponding frequencies at Washington. Thus in Figure 7 the 2398-kc effective height rises faster in December 1932 at Boston than does the 4000-kc effective height at Washington; similar phenomena are exhibited in Figure 8 for April 1933.

At the maximum height of the ray-path and for vertical reflections (or rather refractions)

$$0 = n = 1 - Ne/mw^2 \quad \text{or} \quad Ne/mw^2 = 1 \qquad (1)$$

where n is index of refraction, N is electron-density, m is electron-mass, e is electron-charge, and $w = 2\pi$ (frequency).

It is clear that during the winter evening-hours the electron-density indicated

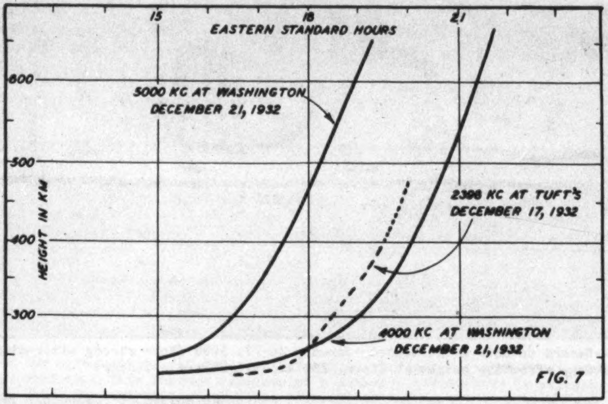

Fig. 7--Comparative Kennelly-Heaviside layer heights for Boston, Massachusetts, and Washington, D. C. (Note earlier rise and disappearance of 2398-kc reflections at Boston while reflections persist until after midnight on 4000 kc at Washington, D.C.)

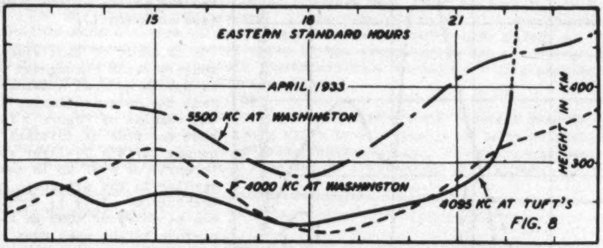

Fig. 8--Comparison of average afternoon and evening variations of virtual height for early April 1933 on 4095 kc at Boston and 4000 and 5500 kc at Washington, D. C. (Note more rapid rise of layer during evening and virtual-height maximum in earlier afternoon at Boston)

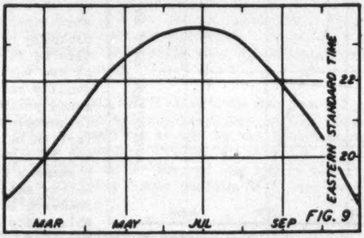

Fig. 9--Kennelly-Heaviside layer reflection average time of cut-off for Boston, Massachusetts, during year 1933 for 4095 kc

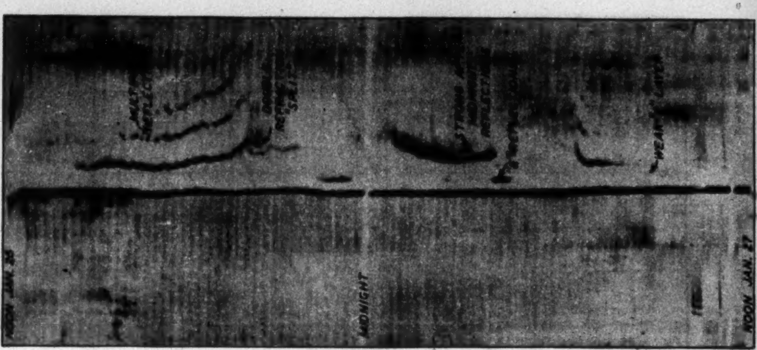

Fig. 10--Record on 2398 kc at Boston, January 26-27, 1933 (Note strong after-midnight ionization; effective height at 3 p.m. 230 km; height-scale linear)

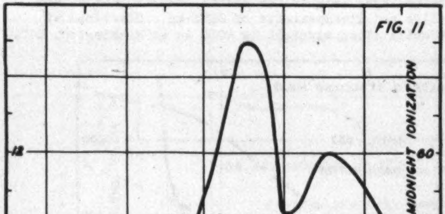

FIG. 11

Fig. 11--Comparison of frequency of occurrence of reflections late at night and of meteor-rates

at Boston is frequently less than half that at Washington, for this ratio is equal to the square of the critical-frequency ratio for the two points at the given time (see equation 1).

A curve of this electron-density ratio throughout the day is not in general attainable from the data available, although the results of Figure 8 indicate that the time of critical frequency for the F_1-layer at Boston in April on 4095 kc is much earlier in the afternoon than at Washington. This is indicated by the tendency of 4095 kc to show a maximum height near noon at Boston, while its maximum occurs at about 3 p.m. at Washington. This indicates a consistent tendency to a lower electron-density at Boston through the day. Were it not that different forms of electron-height distributions probably result in different ratios of virtual to true height at the two points, the electron-density ratio could be determined at any time by finding two frequencies giving the same effective height. However, E-layer and F_1-layer critical-frequency phenomena do not permit us to safely employ such criteria. However, at the time of cut-off this ratio may be accurately determined.

This time of cut-off for 4095 kc at Boston is shown in Figure 9 for the year 1933.

Available published data for Washington are not as yet sufficiently complete to permit the ratio of electron-densities at Boston time of cut-off to be computed for all seasons for the two points, but utilizing data from figures in the paper by Kirby, Berkner, and Stuart previously noted, values of the order of 3:1 and 2.5:1 are obtained for the ratio of Washington electron-density to Boston electron-density for 9 p.m. in December 1932 and April 1933, respectively.

Another interesting phenomenon associated with the Kennelly-Heaviside layer series at Boston relates to the frequent appearance of increased ionization for a period after midnight. The courses of this phenomenon, which is clearly shown in Figure 10, are not entirely clear, but the result of the series in 1933 give support to the suggestion of Schafer and Goodall (Observations of Kennelly-Heaviside layer heights during the Leonid meteor-shower of November 1931, Proc. I. R. E., v. 20, pp. 1941-1945, 1932) that this phenomenon is closely associated with meteors, which in general attain their maximum hourly rate in the hours following midnight. Thus, in Figure 11 a curve showing the percentage of available daily records taken by months (for frequencies above 3000 kc) and showing this phenomenon in the year 1933, is compared with mean frequencies for monthly meteor-rates as obtained by Olivier (see average values of rates obtained from p. 182 of Olivier's "Meteors," 1928).

While the agreement is far from perfect, it is sufficiently good to suggest a strong correlation. This further evidence of a meteoric correlation is particularly gratifying since the original conclusions reported in the series of Schafer and Goodall embraced but a single shower during November. However, a still longer series of observations is necessary before a reliable statistical conclusion relative to the degree of correlation between these phenomena can be deduced. From the lack of detailed coincidence of the curves, it seems probable that other factors may in part be responsible for the observed ionization. A more complete study of these phenomena will be possible when a series of continuous records extending over a band of frequencies becomes available. A modification of the transmitting and receiving equipment at Boston to permit more complete characteristics through use of a continuously varying transmitted frequency is in preparation.

The writers wish to express their appreciation of grants received from the Rumford Fund and the Permanent Science Fund, which have respectively made possible the construction and maintenance of the Kennelly-Heaviside layer recording-equipment utilized in obtaining results in part reported in sections of this paper.

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AUDIO-FREQUENCY ATMOSPHERICS

E. T. Burton and E. M. Boardman

A year ago one of us presented a paper (E. T. Burton and E. M. Boardman, Audio-frequency atmospherics, Proc. I. R. E., v. 21, pp. 1476-1494, 1933) a feature of which was some sound-records of musical atmospherics. Since that date additional records have been obtained. Before proceeding with the demonstration of these records it would be well to review the subject.

Audio-frequency atmospherics may be divided into two general groups, musical and non-musical. The non-musical atmospherics appear much as does detected radio-frequency static. They consist audibly of rumbling sounds in the low-frequency, crackling in the intermediate-frequency, and frying or hissing in the high-frequency range. These sounds contain little that is striking to the ear and may be passed with brief comment. Sounds which possess a definite tonal quality have been termed musical, and with them this paper is concerned.

The earliest reported observations of musical atmospherics to come to our attention were made in 1894 by W. H. Preece of the British Post Office. He describes listening tests made with telephone-receivers connected to their lines during a magnetic storm. Sounds heard were evidently those known by us as swishes. He concludes that the sounds "...... accompanied or were consequent on sunspots, earth-currents, and the aurora."

Since that date there have been other observers. H. Barkhausen during the war observed tones which apparently were swishes. T. L. Eckersley of the Marconi Company in England has made a very thorough study. He groups the sounds into two classes, namely, long and short whistlers.

Members of the Bell Laboratories staff have observed the sounds on submarine cables, in Newfoundland in 1929, in Ireland in 1930-31, and in Cuba in 1931. A submarine cable is a very poor antenna for the reception of these atmospherics, and the study of them was only incidental to other work. Since then observations have been made using loop-antennas in New Hampshire during the solar eclipse of 1932, in New Jersey, and again last summer in New Hampshire when some of the records to be demonstrated were made.

Two general types of these sounds were heard and given the names "tweek" and "swish". The tweeks are without doubt Eckersley's short whistlers and the long whistlers correspond to certain types of swishes.

The tweek is a damped oscillation of descending frequency, of less than one-eighth second audible duration, originating in and trailing a static impulse. Its frequency-descent is rapid and approaches an asymptote which may be between 1600 and 2300 cycles per second. The initial frequency is variable, and has been observed to range from 2000 to in excess of 4000 cycles per second.

The tweek is a night-time phenomenon. Near sunset, static impulses appear trailed by very highly damped tones. As darkness approaches, the damping gradually decreases and the proportion of static impulses trailed by tone increases until steady night-time conditions obtain. These sounds continue throughout the night, frequently increasing in amplitude and number just before daybreak. During the morning twilight the tweeks reduce rapidly and cease to exist near sunrise.

The tweek limiting frequency is subject to change. The first tweeks appear aurally to be asymptotic to approximately 2300 cycles. As the evening advances this limit slowly reduces and during complete darkness may remain in the vicinity of 1600 cycles. During morning twilight a rapid rise is noted, until the tone is lost in the vicinity of 2300 cycles.

Since tweeks seem to derive from static impulses, seasonal variations are to be expected. During the winter their rate of occurrence may be less than one per minute while in the summer the rate may exceed the counting ability of an observer. [A demonstration of tweek-record was made here during presentation of paper.]

The tweek may be explained as the result of a momentary electromagnetic disturbance being propagated to the receiver as a series of impulses. This series might result from multiple reflections of the original disturbance between the Earth and a reflecting layer in the upper atmosphere. Such a series would possess the characteristics of a tweek.

The change in tweek-frequency during twilight periods may be interpreted as a change in the effective height of the reflecting layer. By this theory the layer-height near sunrise or sunset appears to be about 61 km and during complete darkness to be about 88 km.

Failure of tweeks to appear during daylight may be attributed to a low-altitude damping region maintained by sunlight, which region forms rapidly at sunrise, and disintegrates slowly after sunset.

The swishes comprise a large family of sounds, the more prominent of which will be described:

(1) One type is a whistling sound of rather pure tone, of almost constant amplitude and of descending frequency. The upper frequency is well above 4000 cycles and

the lower below 800 cycles. This tone has been observed by us to vary in length from a fraction of a second to about five seconds, and by others to be even longer. Frequently these sounds occur regularly spaced in trains, suggesting echoes. Generally, in a train, the swishes progressively decrease in amplitude, but we have observed cases where the amplitudes increased regularly. Preceding this type of swish by from one to three seconds, a distinctive static impulse has often been heard. The correlation between the two is definite.

(2) Reversing swishes have been observed. Either the ascent or the descent may be first. The ascent is quite rapid and the descent comparatively slow.

(3) Isolated ascending swishes of short duration are common. A relationship between ascending and descending tones seems established by the existence of the reversing swish and by observation-periods during which a large number of the ascending variety were heard, always coincident with the first of a train of the descending variety.

(4) The swish of the type to which the name was first given is less distinctive than those just described in that the tones are accompanied by a prominent rushing sound. A similar disturbance would be created by a varying number of thin wires drawn through the air at different rates. The sound possesses a certain amount of fluctuating continuity. Generally the variation in tone, either upward or downward, is over a range of only a few hundred cycles, but is not confined to any one portion of the voice-range. This type of swish is probably the most generally observed.

(5) A variety of sound which seems related to the swish appears in the range from 500 to 1500 cycles. While not distinctive enough to be striking to the ear, it may be of considerable amplitude.

[Demonstration of several swish-records were made here during presentation of paper.]

During a swish-storm a wide variety of the sounds are generally heard. At any given time, however, a preponderance of a single type is usual. During disturbed periods a somewhat gradual progression from one type to another has been noted.

As previously noted, Mr. Preece was definitely convinced of a connection of the swish-sounds to aurora and earth-current variations. Our observations have indicated that such a correlation may exist.

During the tests in Newfoundland aurora was observed during one evening. It was not of the flashing type and no swish-tones were noted. However, during the New Hampshire tests of 1932, an auroral arc in the north was observed. Near the northwest end, frequent weak flashes were seen, and a similar but still weaker flashing occurred in the southwest. At times the flashing appeared to extend along the entire western horizon. It was observed that nearly every flash coincided with the distinctive type of static crash preceding a swish.

Of special interest are reports from many observers testifying that during displays of low-altitude auroras they have heard accompanying sounds. These sounds come directly from the air, and are heard without the aid of apparatus. Professor S. Chapman, reviewing the testimony of several observers, quotes their descriptions as: "Quite audible swishing, crackling, rushing sounds"; "Similar to escaping steam, or air from a tire"; "To the lash of a whip being drawn through the air"; "A flock of birds flying close to one's head". These descriptions could be equally well applied to swishes.

Dr. J. Leon Williams, another observer, says that he has heard "swishing" sounds and that in his experience they only accompany an auroral display of a type where "tall, waving columns with tops reaching nearly to the zenith were moving across the sky".

No measurements of earth-currents were made by us during the tests in Ireland. Attempts to correlate observations taken there with corresponding earth-current data obtained in this country have been unsuccessful.

During the New Hampshire tests of 1932 a swish-storm existed. The United States Magnetic Observatory at Tucson, Arizona, reports a magnetic storm beginning August 27 and slowly reducing to a low level on September 1, 1932. We observed high-intensity swish from the evening of August 30, when observations began, to September 1, 1932. From then until the morning of September 2 the swish-intensity appeared to be reducing.

The New Hampshire observations of 1933 extended through a swish-storm. Again swish-intensities were compared with data from the Tucson Observatory and in addition with data from the Cheltenham Observatory in Maryland. The magnetic storm extended from August 12 to 27, 1933, and the swish-disturbance from August 15 to 29. Aside from this apparent lag of the swish-storm, the data for swish appear to correlate with the two sets of magnetic data about as well as the Tucson and Cheltenham data agree with each other.

Usually our observations have been made with the aid of vacuum-tube amplifiers, supplemented by electrical filters for restricting the frequency-range to be studied. The restriction of the frequency-range is useful in reducing the masking effect of one type of atmospheric upon another. Amplifying apparatus may be dispensed with if a sufficiently large antenna is provided. In Ireland on an open wire, ground-return telephone-line, we have heard the musical atmospherics with an amplitude as great as speech on the same line.

If the theory proposed to explain tweeks is correct, several possible uses may be suggested. Determination of the lower limiting-frequency will give a measure of the virtual height of the Kennelly-Heaviside layer at audio frequencies. By making directional measurements it would be possible to locate and follow an electrical storm. In addition to determining the direction, a knowledge of the time-spacing of the first tweek-pulses would allow a computation of the distance from the observer to the disturbance.

Swishes provide an even wider field for speculation and study. That they result from multiple reflections of an impulse between ionized atmospheric layers seems improbable. Possibly they indicate, as has been suggested by others, the existence of a highly dispersive region. It is possible that the oscillations may be generated at the source. In any event means seem to be provided for study of the upper atmosphere and its transmission-properties.

The need for an extended study of these musical atmospherics seems to be indicated. If a correlation exists between these sounds and other phenomena of terrestrial magnetism and electricity, a useful line of investigation may be open to the geophysicist.

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New York, New York

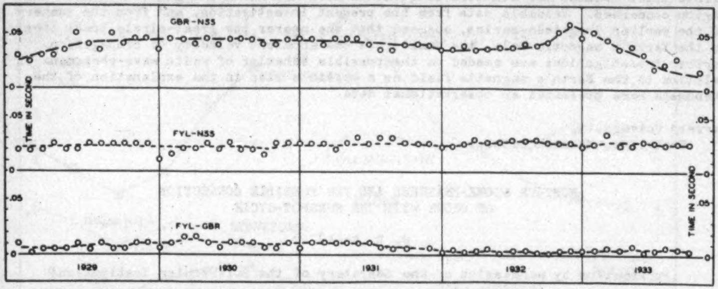
FURTHER STUDIES OF RADIO TRANSMISSION IN GEOPHYSICAL INVESTIGATIONS

Harlan T. Stetson

At previous meetings of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union, the apparent correlations of the intensity of radio reception with solar activity and the positions of the Moon have been reported, adding some further evidence to the interrelation of radio transmission to cosmic phenomena.

In earlier reports to the Section of Geodesy of the Union, small variations in latitude and longitude have likewise appeared to correlate with the position of the Moon at the time star-observations are made.

As a by-product of the study of differences in time-determinations between Washington and Greenwich, reported by Loomis and Stetson in the "Monthly Notices of the Royal Astronomical Society" for April 1933, the transmission-times have been calculated from the published corrections in accordance with equations given on page 48 of the Transactions of the annual meeting in 1933 of the Union. Mean monthly values of the transmission-time have been taken for each pair of stations used in the intercomparison of signals.



MONTHLY MEAN VALUES OF APPARENT TIME OF PROPOGATION OF 17-KILOCYCLE TRANS-ATLANTIC TIME-SIGNAL

A study of the curves in the accompanying graph indicates a considerable variation in the time of propagation over the Rugby-Annapolis (GBR-NSS) path during the last five years, the value at the beginning of 1929 being near the theoretical value. During 1930 and 1931 the propagation-time was nearly $0^{\mathrm{s}}.04$, followed by a dip in the early part of 1932 and a sharp rise at the end of 1932, with an unexplainable fall in the apparent time of propagation during the past year indicating at the close of the year a velocity of the wave nearly equal to the velocity of light as might be expected. During the same interval the time of propagation between Bordeaux and Annapolis (FYL and NSS) has remained remarkably near the constant value of $0^{\mathrm{s}}.025$ for the 6163-km trans-Atlantic path. It is suggested that peculiarities in the Annapolis-Rugby (NSS-GBR) path, of 5793 km, may be due to the greater effect of the magnetic field of the Earth on the more northern route. A comparison of the propagation-time between Bordeaux (FYL) and Rugby (GBR) indicates again an apparently large retardation of the radio waves during 1930 and 1931 on the France-England route.

Apropos of the results here represented, an investigation has been made of the times of propagation of the radio waves between cooperating stations in the world-wide longitude-campaign of 1926, as reported in the papers of the General Assembly of the International Scientific Radio Union for 1928 (v. 2). Table 1 is an illuminating summary. From the time of propagation of signals between the stations indicated the apparent wave-velocity was deduced. From this velocity the equivalent time for transmission of the wave completely around the Earth was calculated. The tabulated values then give a common basis for comparison of relative velocities of different paths. All of the above data are for long waves of the order from 17,000 to 18,000 meters. On the Vancouver - Washington comparison 37-meter waves gave an equivalent time of transmission around the Earth of $0^{\mathrm{s}}.158$, suggestive that the high-frequency waves travel at a somewhat greater velocity. The wide discrepancies in the apparent wave-velocities dependent on the transmission-path suggested a comparison of the great-

Table 1

Stations	Transmission-time around the Earth
San Diego - Tokyo	$0^{\mathrm{s}}.121$
Washington - Tokyo	0.137
Greenwich - Tokyo	0.160
Vancouver - Washington	0.163
Greenwich - Washington	0.168
Tokyo - Paris	0.175
San Diego - Washington	0.178
Vancouver - Tokyo	0.211
Greenwich - Ottawa	0.259
Ottawa - Tokyo	0.311

circle track between the stations in question with the Earth's magnetic field in the region concerned. Valuable data from the present investigation, and from the summary of the earlier longitude-series, suggest that the nearer the great-circle track lies to the Earth's magnetic pole, the smaller is the apparent velocity of propagation. Further investigations are needed on the possible behavior of radio wave-phenomena in relation to the Earth's magnetic field as a possible step in the explanation of the phenomena here presented as observational data.

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Cambridge, Massachusetts

FURTHER OZONE-MEASURES AND THE POSSIBLE CONNECTION OF OZONE WITH THE SUNSPOT-CYCLE

F. E. Fowle

(Publication by permission of the Secretary of the Smithsonian Institution)

This is a third report on atmospheric ozone. The measure used is the amount of solar radiation absorbed in the Chappuis ozone-band as observed at ground-level were the Sun in the zenith. This band extends in the spectrum roughly from 0.45 to 0.65µ. The stations furnishing the observations presented here are: Montezuma, Chile, in latitude 22.°7 south at elevation 2711 meters above sea-level (in the Andes); Harqua Hala, Arizona, in latitude 33.°8 north at elevation 1721 meters above sea-level; and Table Mountain, California, in latitude 34.°4 north at elevation 2286 meters above sea-level. It will be noted that Harqua Hala and Table Mountain are at nearly the same latitude.

A better understanding of the significance of this report may result by first giving the present state of the ozone-problem and then turning to the developments of the author's three reports. Dr. Chalonge gives a resumé entitled "L'etat actuel du problème de l'ozone atmospherique" (Bull. bi-menseuel, Soc. franc. physique, No. 349, p. 16, 1934), which will serve this first purpose in the following abbreviated form:

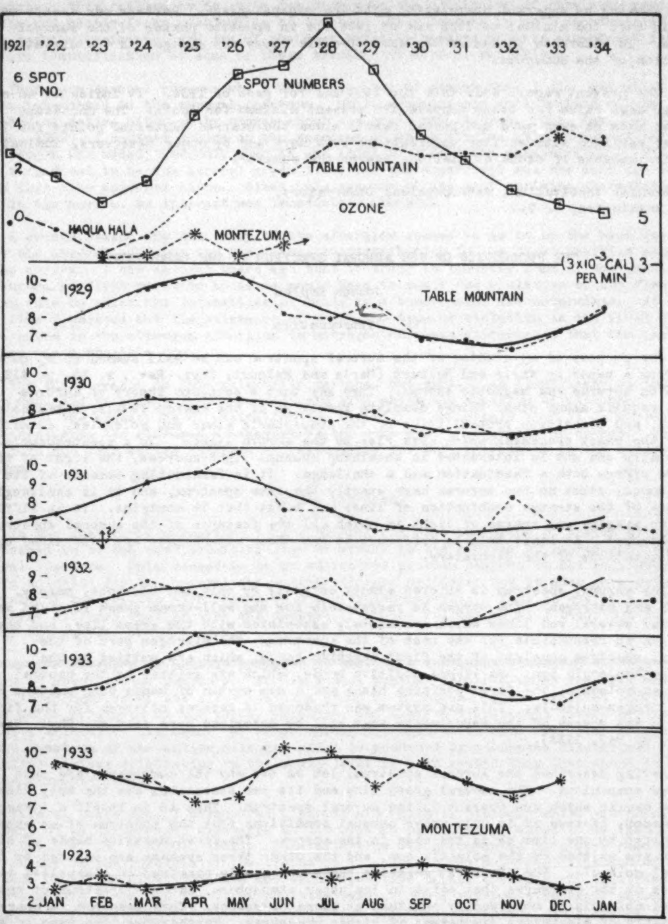
(a) Ozone is produced in the upper layers of the atmosphere--it may be by the action upon oxygen of the ultraviolet radiation from the Sun of wave-length less than 2000 Å, or by electrons, or more generally by electrified particles which make up the auroral discharge. Various agents hinder the accumulation of ozone, namely, solar ultraviolet light of wave-lengths between 2200 and 3400 Å, the relatively high temperatures at altitudes of about 50 km, and the presence of water-vapor and ammonia at low altitudes.
(b) Chalonge and Götz indicate an increase during the night.
(c) The height and distribution in height is still doubtful. At first considered as located in a band at about 40 km, there has been a disposition to lower this height and widen the band. The methods used do not lend themselves to much accuracy.

There may be added two generally conceded characteristics:

(d) Ozone is generally the greatest in amount during the spring months and least during the autumn; it therefore reaches these singular points at opposite times of the year in the northern and southern latitudes.
(e) The amount of ozone is least at the equator and increases towards the poles.

In his first report the writer thought the run of his data could indicate that there might be two sources of the ozone. These could be taken as due to the aurora and the ultraviolet light, respectively.

The accompanying Figure is shown in three sections. The middle section shows the monthly mean values for several years of the ozone above Table Mountain and, with the similar values in the bottom section for Montezuma, illustrates the law shown above under characteristic (d). The top section shows the run of several phenomena with the abscissae as years, from 1921 to 1934. The uppermost graph gives the Wolfer sunspot-numbers. Next below runs the course of the ozone-graph, the absorption of solar energy



in the red band running from about 3×10^{-3} to 9×10^{-3} calories per min. In my first report (Smithsonian Misc. Collections, 81, No. 11, 1929) only the data on ozone for Table Mountain from 1921 to 1928 were known and, as it stands, certainly indicates a close correlation with the sunspot-numbers. The starred points for Montezuma are much less accurate but they also show a general slight increase with increasing ozone.

The second report (Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 110-111) included points for 1929 to 1932, inclusive, for Table Mountain. We find them showing no apparent correlation with the sunspot-graph. Perhaps our escape may lie in that the minimal of 1923 and of 1934 lie in opposite phases of the sunspot-cycle. In alternate phases of the sunspot-cycle there are changes in the direction of rotation of the sunspots.

The present report adds data for 1933 and for part of 1934. It indicates an even higher mean value for ozone despite the present minimum for spots. The Montezuma values show an even more unexpected result since the starred Montezuma points for 1933 are at variance with earlier observations both here and by other observers, indicating smaller amounts of ozone at stations nearer the equator.

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Washington, D. C.

THE PRODUCTION OF THE AURORAL SPECTRUM IN THE LABORATORY

Joseph Kaplan

Introduction

The purpose of my studies of the auroral spectrum can be well summed up by quoting from a paper by Maris and Hulburt (Maris and Hulburt, Phys. Rev., v. 33, p. 412, 1929) on aurorae and magnetic storms. They say that a complete theory of auroras "will require among other things complete knowledge of the energy levels, metastable states, and transition probabilities of the atmospheric atoms and molecules, as well as of the exact processes which give rise to the aurora light." To a spectroscopist, especially one who is interested in obtaining unusual light-sources, the light of the aurora offers both a fascination and a challenge. It is fascinating because of its fickleness, since no two auroras have exactly the same spectrum, and it is challenging because of the strange combination of lines and bands that it contains. It is difficult to imagine one source of light in which all the features of the auroral spectrum are observed. At least this is difficult to one whose experiences are determined by the limitations of the laboratory.

The auroral spectrum is emitted almost entirely by only two elements, namely, oxygen and nitrogen. The oxygen is responsible for the well-known green line and perhaps for several red lines which are closely associated with the green line, and the nitrogen is responsible for the rest of the spectrum. The nitrogen part of the auroral spectrum consists of the first negative bands, which are emitted by the nitrogen-molecule ion; the second positive bands, which are emitted by the neutral nitrogen-molecule; the first positive bands and a new system of bands both emitted by the nitrogen-molecule. This new system was produced in gaseous nitrogen for the first time in the course of the experiments that will be described here (Kaplan, Phys. Rev., v. 44, p. 947, 1933).

Having described the auroral spectrum, let us see why its components are such strange companions. The auroral green line and its red associates are the only lines due to oxygen which are present in the auroral spectrum. This is in itself a strange phenomenon, because it is only under unusual conditions that the spectrum of an atom is limited to one line as is the case in the aurora. The first negative bands of nitrogen are emitted by the molecule ion, and the other three systems are emitted by the neutral molecule. Now the first negative bands are easily obtained in electrical discharges at the pressures that exist in the upper atmosphere, but the spectrum of the neutral molecule is not readily obtained at those pressures. That spectrum is characteristic of electrical discharges at higher pressures. Furthermore, the type of excitation of the first positive bands which is present in the aurora does not agree with excitation in the electrical discharge. It is certainly impossible to simply pass a discharge through nitrogen at very low pressures and obtain the nitrogen part of the auroral spectrum, or to do the same for a nitrogen-oxygen mixture and obtain the entire auroral spectrum.

Still another aspect of the problem should be described. The auroral spectrum contains some weaker and yet extremely important radiations which fall in the green, yellow, red, and infra-red, and which are difficult to identify with a great degree of certainty. This failure to do so is due partly to the difficulty of obtaining good spectra and partly to an overlapping of spectra. This feature is well demonstrated in the present experiments, and one of the most striking results of this experiment is a positive identification of some of these troublesome auroral radiations.

There are several reasons why I chose the line of attack that I did, and why I became interested in the auroral spectrum. While studying the modification of the spectrum of active nitrogen by oxygen about six years ago (Kaplan, Phys. Rev., v. 33, p. 154, 1929), I noticed a line on the spectrum of the afterglow which appeared only when oxygen was added, and only when it was added in a definite concentration. This line turned out to be the auroral green line, and the experiment was the only one in which this line appeared alone. Since this was one of its most striking characteristics in the aurora, my interest was immediately aroused.

A second reason why the study of the afterglow seemed to me to be the best way to study the auroral spectrum was the intensity-distribution in the first positive bands of the aurora. I saw several years ago that in order to identify some of the bands of the aurora as first positive bands we would have to admit the violation of the Franck-Condon rule by which the intensities of bands in a band-system are determined. At the same time I pointed out the existence of this same type of violation in the first positive bands in the nitrogen afterglow in nitrogen-rare-gas mixtures so that the phenomenon was a possible one.

The third reason is less scientific perhaps, but equally as significant as the other two, and it arises from the readiness with which the spectrum of nitrogen changes as the conditions of excitation are varied. I am certain that it is correct to characterize the nitrogen discharges as the ones most susceptible to change. It will turn out that active nitrogen is responsible for this fickleness in the nature of nitrogen.

Active nitrogen

In the last three paragraphs I have pointed out that the study of active nitrogen seemed to be the most promising line of attack on the problem of reproducing the auroral spectrum. This seemed to be an attractive problem because it not only promised a solution for the auroral and active-nitrogen problems, but it also gave promise of yielding new results with regard to the nitrogen-molecule. Thus it was to a study of active nitrogen that my time was devoted. In what follows we will point out only a few of the results of that work.

Active nitrogen is usually produced by passing a condensed discharge through nitrogen at about 0.5-mm pressure. It has a most unusual spectrum which consists mainly of selected members of the first positive group of nitrogen. These selected bands are those which originate on the tenth, eleventh, and twelfth vibrational levels of the so-called $A^3\Sigma$ level of nitrogen. No other strong nitrogen-bands have ever been observed in the spectrum of the active nitrogen which is produced by condensed discharges. The so-called maximum originating on the sixth level is much weaker than that which is due to the eleventh level.

Several years ago, I discovered a strong afterglow of nitrogen which was produced by means of an uncondensed discharge in nitrogen at pressures of about 10 mm (Kaplan, Phys. Rev., v. 37, p. 1004, 1931). This afterglow was accompanied by a very remarkable change in the spectrum of the discharge in which it was produced. Instead of being made up of the first-positive and second-positive bands, the spectrum consisted of first-negative bands and the first-positive bands. The first-positive bands which originated on very high vibrational levels were very much enhanced. This change in the spectrum occurred only when the afterglow was present, and the stronger the afterglow the more thorough this change became. In the ultraviolet this discharge contained a new system of bands which was identical with a system observed by Vegard in the luminescence of solid nitrogen (Vegard, Skrifter Utgitt an Det Norske Videnskaps Akad. i Oslo, v. 2, p. 24, 1930), and three members of which agreed closely with three hitherto unidentified bands in the auroral spectrum.

The tube in which all the above phenomena occurred showed rather remarkable color-changes as the conditions of excitation varied. Two stages were particularly

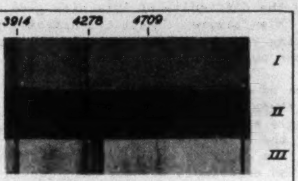

FIG. 1

I SPECTRUM OF THE AFTERGLOW
II. SPECTRUM OF THE DISCHARGE
III AURORAL SPECTRUM

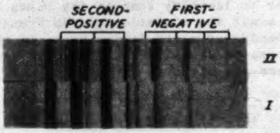

FIG. 2

I. DISCHARGE
II. AFTERGLOW

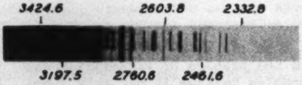

FIG. 3

NEW BANDS IN N_2

prominent, a green stage at low current and a blue stage at higher current. The greenish-white color in the first stage and the blue-white color of the second stage correspond very closely with the most common auroral colors.

The afterglow which accompanies the green stage is so different than that which accompanies a condensed discharge that it really should be considered to be a new afterglow in nitrogen. This is also true for the other stages of the discharge, but to a lesser extent. In fact, the higher the current through the tube the more like the normal afterglow does this afterglow in uncondensed discharges become.

The spectrum of the afterglow when the tube was operated in the green stage is shown in Figure 1. It was taken on an Eastman astronomical green plate. The most prominent bands in this spectrum are not the first-positive bands that originate on the tenth, eleventh, and twelfth vibrational levels of the $B^3\pi$ state, but the first-negative bands of N_2^+ and those first-positive bands that originate on the v' = 15-, 16-, 17-, 18-, and 19-levels. The spectrum of the discharge itself is shown in the same Figure. It is to be noted that this spectrum resembles that of the afterglow very closely. The main differences between the two are the enhancement of the first-negative group relative to the first-positive group, and the enhancement of the first-positive bands that originate on very high vibrational states with respect to those that lie on lower states.

In the third spectrum in Figure 1 there is shown a spectrum of the aurora as taken by Slipher. A comparison of this spectrum with that of the afterglow will show the remarkable similarity between the two. The similarity between the afterglow and the auroral spectrum is more striking than that between the discharge and the auroral spectrum. The first-positive bands in the discharge, especially the ones originating on the lower vibrational states, are more intense relative to the negative bands than they are either in the afterglow or the aurora.

Vegard (Vegard, Geofysiske Publikasjoner, v. 10, No. 4, p. 38) has reported first-positive bands in the aurora with wave-lengths 5001 Å and 5241 Å, and has interpreted these as the first-positive bands (15,10) and (16,11). These bands form a prominent feature of the new afterglow and their presence in the afterglow in the company of the negative bands not only corroborates the identification proposed by Vegard, but it justifies the claim that the auroral spectrum has been reproduced in the laboratory. Similar statements could apply equally as well to other auroral radiations whose interpretations have hitherto been in doubt but are now definitely made.

A word should be added here as to the connection between the first-positive bands in the afterglow and the spectrum of the luminescence of solid nitrogen. Four prominent bands or sets of bands have been observed in the spectrum of the luminescence of solid nitrogen, and they fall in the region where these high first-positive bands lie. I have identified these as members of the first-positive system, and I have also pointed out the remarkable agreement between them and some auroral radiations (Kaplan, Phys. Rev., v. 42, p. 86, 1932). In the present afterglow the first-positive bands are remarkably like the N_1, N_2, N_3, and N_4 bands of the solid luminescence, and this resemblance justifies my identification of these bands as well as the notion of a resemblance between the solid luminescence and the auroral spectrum, as unlikely as this resemblance may have seemed offhand. It must be remarked here that Vegard pointed out this resemblance but on far less certain evidence. Vegard, however, has failed to identify the four bands in the luminescence of solid nitrogen as first-positive bands.

Spectrum 2 of Figure 2 shows once more the resemblance between the afterglow and the auroral spectrum. This spectrum of the afterglow was taken on a small Hilger quartz-spectrograph and Eastman 33 plates. It is seen that the second-positive bands are also present in the afterglow, and a comparison of spectrum 2 with that of the discharge in spectrum 1 will show that the main difference is that the first-negative bands have increased in intensity relative to the first-positive bands, and in fact the relative intensities of these two systems in the afterglow is remarkably like that reported for auroral displays.

We now leave the afterglow for a moment and point out another remarkable resemblance between the spectra, observed in the present experiment, those of the luminescence of solid nitrogen, and the spectrum of the aurora. The two auroral bands 3203 and 3429 were recently identified by Vegard as members of the so-called b'-series which he observed in the luminescence of solid nitrogen. In the same portion of the discharge-tube in the writer's experiments in which the new afterglow was observed there was discovered a new system of nitrogen bands which coincide with members of the so-called ε-system observed by Vegard in the luminescence of solid N_2 and heretofore unobserved in gaseous discharges. Two members of this system, the band 3424.6 and the band 3197.5, are undoubtedly the two auroral bands mentioned above. Figure 3 shows these new bands. The rather surprising connection of these three spectra furnishes food for much thought and discussion, but the limitations of this paper do not permit any more to be said about it.

Discussion

The similarity between the afterglow-spectrum and the auroral spectrum on the one hand, and between the discharge and the afterglow on the other hand, leads one to the conclusion that an auroral display is a sequence of discharges and afterglows. When one looks for a reason for the similarity between the afterglow and the discharge, only one reason presents itself. It is now generally recognized that a metastable state of nitrogen is responsible for the afterglow, and hence we conclude that the unusual spectroscopic phenomena that take place in the part of the tube in which the afterglow is present must be traced to the presence of metastable molecules. It may be recalled that metastable states are those from which the atom or molecule can only seldom radiate. In nitrogen the $A^3\Sigma$ level has for a long time filled the rôle of being a metastable state. The discovery of the new nitrogen-bands mentioned earlier in this paper changes the situation with regard to the metastable state of nitrogen, but it still provides for one and that is all that is required for the present discussion. If the entire nitrogen-gas in the tube consisted of these metastable molecules then there would be no difference between the discharge spectrum and that of the afterglow, since the afterglow represents the light which is emitted when the metastable molecules collide with each other, whereas the discharge represents the light that is emitted when not only metastable molecules are excited but normal molecules as well. In the laboratory the number of metastable molecules is limited to a great extent by the walls of the tube, since collisions with these walls destroys these molecules. This limitation is not present in the upper atmosphere, and there we would expect a closer resemblance between the discharge- and the afterglow-spectra. In fact, in the upper atmosphere during an auroral display it would be difficult to distinguish between the afterglow- and the direct discharge-spectra. Due to the large number of metastable molecules the afterglow will be much stronger than it is in the laboratory, and this supposition is supported by the observation that even in the laboratory the first stage of the afterglow is a flash that has the same shape as the discharge, indicating that the afterglow processes were going on in the discharge itself. Thus, the present afterglow can be looked on as an indication of what the spectrum of a pure metastable gas would be like.

Many more pictures will be required before a complete knowledge of this new afterglow will have been attained. One of the most fascinating aspects of the work in progress at the present time is the photography of the discharge and the afterglow in the far red and the infra-red. Also the study of the afterglow when the current is even smaller than in the green stage promises some results that may be of interest in connection with the light of the night-sky, where the concentration of metastable molecules is small. In connection with both the aurora and the night-sky problems, it is planned to study the excitation of oxygen by this new form of active nitrogen.

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AURORAE AND EARTH-CURRENTS

W. J. Rooney

(Abstract)

A comparison of auroral observations and earth-current records from the College-Fairbanks Station during the International Polar Year of 1932-33 shows considerable agreement between the aurora and disturbances in the earth-current records. Coefficients of linear correlation from 0.71 to 0.76 were obtained from the records for 80 clear nights. Effects associated with brilliant isolated auroral displays at College are readily detected in the earth-current records at Tucson, Arizona, and in exceptional cases in records obtained as far south as Huancayo, Peru. Oscillatory disturbances in the earth-current records and moving types of aurora, respectively, seem to show the highest degree of correlation. These results are at variance with some comparisons of magnetic and auroral records which indicate a lack of relationship between the two phenomena.

The complete paper is published in the June 1934 number of the Journal of Terrestrial Magnetism and Atmospheric Electricity.

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PRELIMINARY REPORT ON AURORAL, MAGNETIC, AND EARTH-CURRENT OBSERVATIONS AT CHESTERFIELD, NORTHWEST TERRITORIES, CANADA

J. Patterson

The reduction and tabulation of the auroral, magnetic, and earth-current observations taken at Chesterfield (63° 20' north latitude, 90° 42' west longitude) during the second International Polar Year has reached the point where certain general conclusions may be made from the results. However, some or all may be subject to considerable modification when the reductions are completed.

Between October 1, 1933, and April 30, 1934, aurorae were seen on all except 53 nights, and of these 43 were continuously overcast so that an aurora could not have been seen visually. The McLennan night-sky spectrograph was used from December 5, 1933, to April 27, 1934, as an indicator of aurora, the length of exposure being varied from about 15 minutes for clear nights with strong aurora to two hours for overcast nights. With the exception of a few nights with heavy cloud, or with heavy cloud and high snow-drift, auroral spectral lines were always recorded.

Examination of the visual auroral records shows that the usual nightly display consists of (a) relatively faint bands and arcs running approximately from southeast to southwest during the early hours of the night, (b) increasing activity reaching a maximum at about one hour after local midnight or about magnetic midnight for this station, (c) a gradual decrease in activity with the display moving southward; (d) relatively faint bands and arcs appearing in the early morning hours but running from east-northeast to west-southwest, and (e) faint rays and increasing activity just before sunrise.

Measurement of the minimum height of all auroral forms from 100 parallactic photographs shows that heights between 103 and 106 km occur most frequently. A secondary maximum appears to exist between 114 and 122 km. The mean minimum height is 112 km. This value does not include the heights of several faint bands with minimum heights varying from 160 to 181 km. Maximum heights of rays varied from 170 to 350 km. Only two heights below 80 km were obtained, namely, 71 and 77 km.

Magnetic records at Chesterfield are characterized by large and often rapid fluctuations, particularly in the declination. Daily changes of 4° in the declination are the rule, while changes of 10° are not uncommon.

Comparison of the magnetic records with the visual auroral records for Chesterfield shows a strong, positive correlation. Curves showing the mean hourly declination range for each day during the months of January, February, and March, 1934, and the daily auroral activity for the same period agree closely. The values for the auroral activity depend on the frequency and intensity of the auroral forms and are weighted for cloudiness.

The hourly mean declination during the months of January, February, and March, 1934, shows a westerly drift during the early evening hours, and reaches a maximum value at about 6 p.m. G.M.T., or at about local midnight. This is followed by a rapid drift eastward. This maximum westward value occurs about an hour before the time of the maximum auroral activity; the rapid drift to eastward occurs while the auroral display is decreasing in activity and moving southward.

A close relationship between magnetic and auroral activity is also shown by a comparison of the mean declination-range and the mean auroral character-number for the night hours on 59 nights, when the cloudiness was never great enough to hide aurorae. The maximum hourly declination-range occurs at about local midnight. Comparison of auroral activity with magnetic activity using only those hours during which aurora was visible gives a good positive correlation.

Earth-current records from Chesterfield are characterized by rapid and often large variations. These periods of rapid fluctuation occur simultaneously with magnetic disturbances, and sometimes with auroral disturbances. The correlation between earth-current activity and auroral activity is not as good as between magnetic activity and auroral activity, strong auroral displays occurring without a corresponding earth-current disturbance.

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Toronto, Canada

SOME FACTS ABOUT SECULAR VARIATION OF THE EARTH'S MAGNETISM

Rosendo O. Sandoval

In Bulletin No. 12 of the Astronomical Observatory of Tacubaya the author discussed the secular variation of the declination at our Magnetic Observatory. As it was first installed at Mexico City, then at Tacubaya, then at Cuajimalpa, and finally at Teoloyucan, the values of the declination were all reduced to Teoloyucan. The following is quoted from that paper:

> "The observations made at these places are well represented by
>
> $$D = 8^\circ\ 30' + 44'\ \sin 6^\circ(t - 1910)$$
>
> except the values of the first two years at Cuajimalpa.
>
> "The mean curves for Cuajimalpa and Teoloyucan are in accordance with the values found by
>
> $$D = 8^\circ\ 56'.3 + 3'.77(t - 1915) - 0'.205(t - 1915)^2$$
>
> "From these equations the maximum of declination would be about 1926, but declination has increased till now (July 1930)."

This maximum seems to have been reached in the last two months, namely, January and February, 1934.

D. L. Hazard says (Terr. Mag., v. 37, p. 234, 1932):

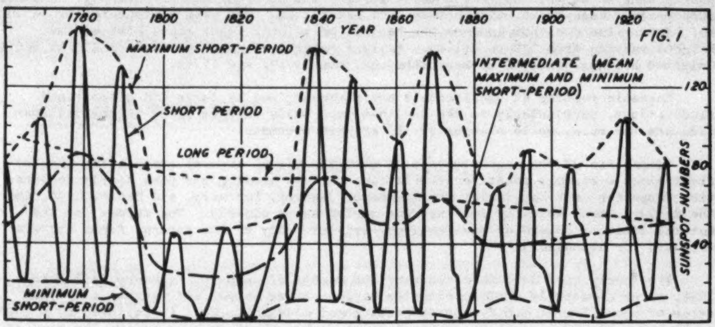

FIG. 1

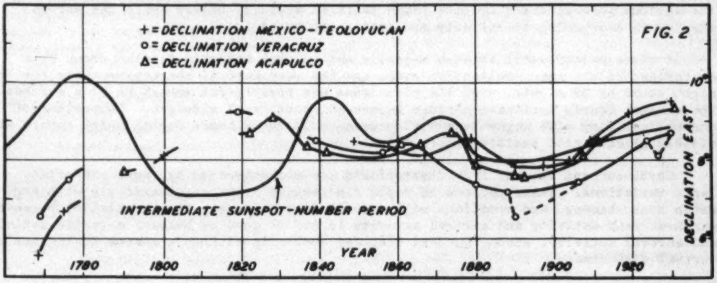

FIG. 2

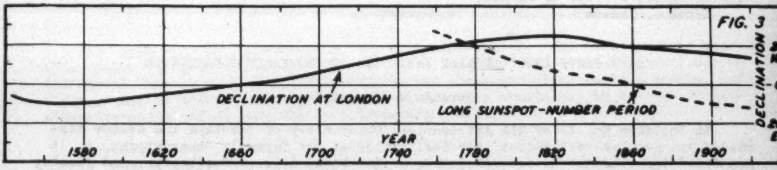

FIG. 3

> "These investigations of Bauer and others showed that little additional knowledge of the secular change could be gained from a further study of the older observations; that only from more homogeneous results could definite conclusions be drawn.........
>
> "With accumulation of more accurate results for identical stations at shorter intervals, it became evident that no simple empirical formula would give a satisfactory representation of the observed changes, that in addition to the broad swing of long period, with definite reversals of the direction of motion, there are variations of a shorter period and smaller amplitude, with points of inflection and subsidiary maxima and minima."

We have seen that no satisfactory representation was obtained with the empirical formula in our case. Must we then wait for years and years? Surely not. I extract from my "Estudio de una onda magnética" (to be published later), an abridgment of which was sent to the Fifth Pacific Science Congress at Vancouver in 1933 under the title

"On a remarkable magnetic wave," the following reasonings not spoken of in the abridgment.

Many graphs have been drawn on several occasions to represent the undecennial periods of sunspots; but they being divided into sections, by their lengthiness, I do not know of anybody to have distinguished two remarkable curves.

Figure 1 shows the undecennial periods of sunspots from 1760 to 1930. We can see that maxima are very high from 1760 to 1790, low from 1800 to 1830, high from 1840 to 1870, and low from 1885 to 1930. The Figure gives graphs also of maxima and of minima and of their mean. The last designated "Intermediate" shows a solar period of about 70 or 80 years. The graph drawn tangent at maxima of the "Intermediate" graph and designated "Long period" shows perhaps a period of 480 or 500 years.

Now, it is well known that the graph showing magnetic activity is parallel to that of the eleven-year period (short period), a representation of which can be seen in "The Earth and the stars" of Charles G. Abbot (p. 112, Fig. 20, ed. 1925).

Then, if the terrestrial-magnetic curve follows the inflections of the short-period graph, it ought to follow the movements of the "Intermediate" and "Long-period" graphs of Figure 1. This seems to be proved by Figure 2, which indicated the "Intermediate" period of Figure 1 and values and graphs of the declination in Mexico for stations Teoloyucan, Veracruz, and Acapulco; it is seen that the graphs are nearly parallel. The same may be said of the declination curves of Cabo San Lucas, Bahía Magdalena, San Bartolomé, and Isla de Cedros, in Lower California, but which are indicated in Figure 2 to avoid confusion. The values of declination before 1850 are very doubtful and incorrect values for 1890 and 1926 in these curves are noted immediately on inspection. Figure 3 shows the same parallelism between the graph for "long sunspot period" of Figure 1 and the curve of declination at London.

These facts seem to be an answer to the unexplained facts mentioned by Mr. Hazard. The three sunspot-periods seem not to be subjected to a regular law that can be interpreted algebraically, and this being so and there being a close relation among graphs of solar periods and declination-curves, it is not possible to establish a formula that will give a satisfactory representation of secular variation. Moreover, an attempt to deduce an empirical formula from the mean of any of the declination-curves, as those of Veracruz, etc., would give an error of about 1°.

It is evident that a greater number of comparisons of the "Intermediate" and "Long-period" sunspot-number graphs with many curves of declination at other stations will make possible confirmation of the author's conclusion in this matter.

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SOME PROBLEMS OF MAGNETIC SURVEYS

N. H. Heck

A--Secular variation for the entire Earth

In the number of the Journal of Terrestrial Magnetism and Electricity for December 1933 (pp. 313-322) there is a report by J. A. Fleming and H. D. Harradon of the meeting at Lisbon of the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics. Among the 23 resolutions adopted which are given, there are three resolutions relating to secular-variation observation. These, among other things, recommend that the governments of all countries undertake a minimum program of magnetic secular-variation work which will provide at least the spacing of repeat-stations recommended by the Association's Committee on Magnetic Secular-Variation. This Committee was formed at the Prague meeting with the writer as Chairman, and with members from France, Great Britain, Poland, Sweden, Denmark, and the United States. It is probable that eventually the Committee's report will be published in the "Proceedings" of the Association for the Lisbon Assembly, but in any case it will not reach all the members of the Section of Terrestrial Magnetism and

Electricity of the American Geophysical Union, so it seems desirable that this important matter be explained here.

The Committee in preparing its recommendations for the Lisbon meeting used as a basis the plan outlined in 1932 by J. A. Fleming, Acting Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington (Distribution of magnetic observatories and secular-variation stations, Terr. Mag., v. 37, pp. 245-251, 1932), and also took into account the investigation of foci as outlined by Harlan W. Fisk in the article entitled "The unsymmetrical distribution of magnetic secular-variation" (Terr. Mag., v. 37, pp. 235-240, 1932).

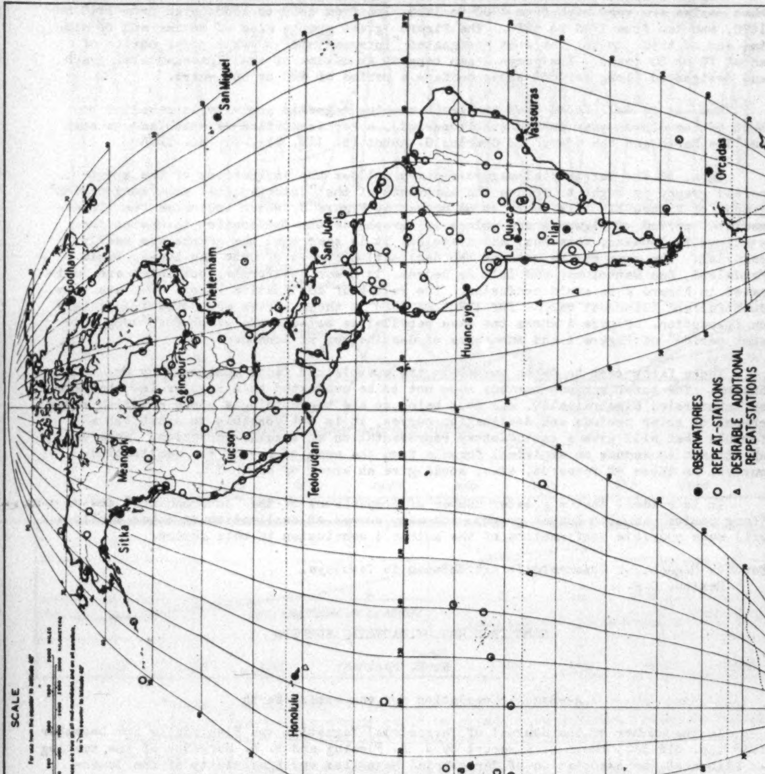
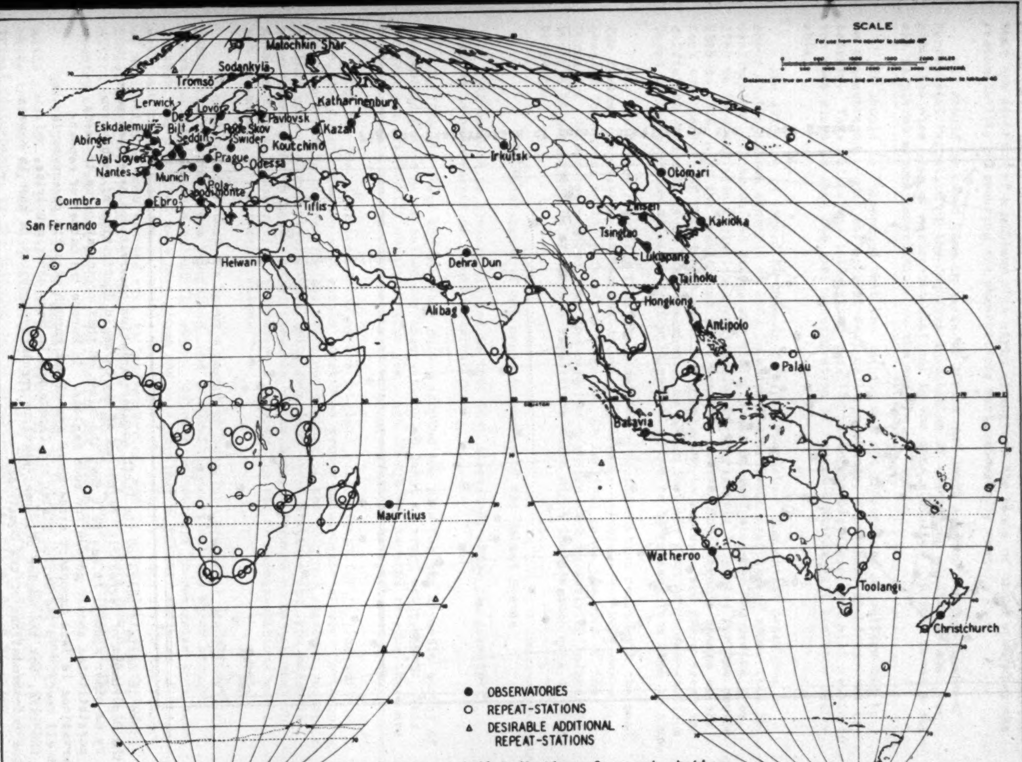

San Miguel
Vassouras
Orcadas
Pilar
La Quiaca
San Juan
Huancayo
Cheltenham
Godhavn
Agincourt
Tucson
Meanook
Teoloyucan
Sitka
Honolulu
Apia
SCALE
● OBSERVATORIES
○ REPEAT-STATIONS
▲ DESIRABLE ADDITIONAL REPEAT-STATIONS

Fig. 1--Proposed distribution of repeat-stations in the Western Hemisphere

The Committee's work, which was carried on by correspondence in the period between meetings, consisted in analyzing Fleming's plan, exchange of suggestions, and finally recommendations. The original maps showing proposed distribution as slightly modified are shown in Figures 1 and 2.


SCALE
For use from the equator to latitude 40°
0 500 1000 1500 2000 MILES
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Distances are true on all real meridians and on all parallels, from the equator to latitude 40
Malochkin Shar
Sodankylä
Tromsö
Lerwick
De Bilt
Lovö
Pavlovsk
Katharinenburg
Eskdalemuir
Abinger
Val Joyeux
Nantes
Seddin
Rude Skov
Swider
Koutchino
Kazan
Prague
Odessa
Munich
Pola
Capodimonte
Coimbra
Ebro
San Fernando
Tiflis
Helwan
Irkutsk
Otomari
Zikawei
Tsingtao
Kakioka
Lukiapang
Taihoku
Hongkong
Dehra Dun
Alibag
Antipolo
Palau
Batavia
Mauritius
Watheroo
Toolangi
Christchurch
● OBSERVATORIES
○ REPEAT-STATIONS
▲ DESIRABLE ADDITIONAL REPEAT-STATIONS

Fig. 2--Proposed distribution of repeat-stations in the Eastern Hemisphere

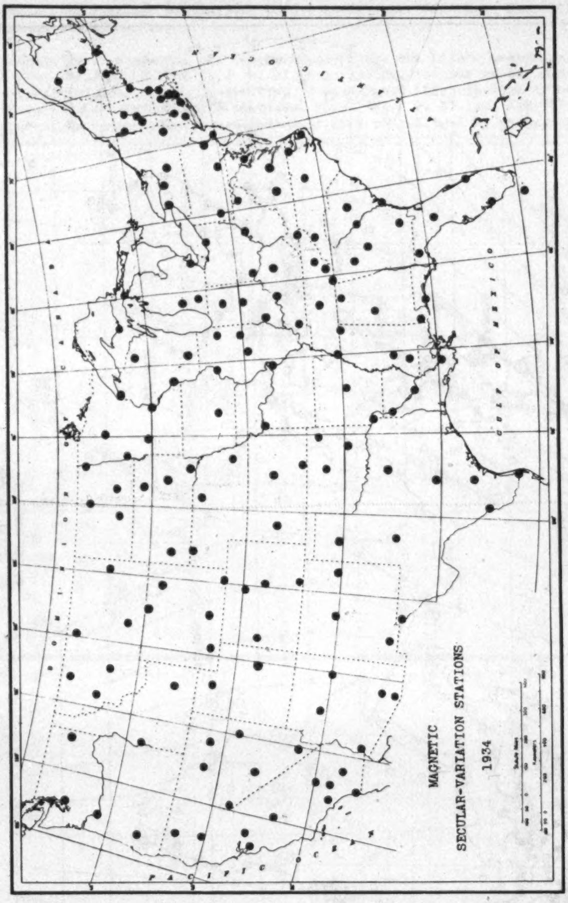

Fig. 3--Distribution of repeat-stations in the United States

Since in certain parts of the Earth secular-variation observations have been made by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and by no other agency, it was felt that the views of that organization as to needs and possibilities should govern for such regions. In Europe the matter of repeat-observations is less important since there are almost enough magnetic observatories to meet all needs. In the United States and Canada and in many other countries, this is not the case, but the number of repeat-stations regularly occupied is much in excess of the recommendations of the Committee.

This leaves large areas where the obtaining of the needed observations is a matter of very considerable difficulty. Much work of this kind has been done in colonial and mandated territories but there are serious gaps. It is the hope of the Committee that the adoption of a minimum plan might strengthen the hands of those upon whom the responsibility of securing the observations must necessarily rest.

It should be noted that in parts of Africa and South America the Department of Terrestrial Magnetism of the Carnegie Institution of Washington adopted in some regions the wise plan of having two stations in the same vicinity. In such cases a circle is placed around the stations on the maps.

It should be understood that the spacing was not intended to be uniform but to be concentrated around the present foci of large change, especially in horizontal intensity. This raises the interesting question as to whether these foci will remain in the same place so that the same concentration of repeat-stations will continue desirable.

The evidence in regard to this is far from complete. The writer presented a paper at the Lisbon Assembly in 1933 in which the probable position of minor foci in declination for the United States and vicinity was investigated for the period from 1750 to 1930 and also a similar investigation for horizontal intensity for the period 1845 to 1925, with the result that there seems to be very considerable change of the foci over periods of this length. If this conclusion is correct, and there seems insufficient reason to doubt its correctness, it seems that any plan of repeat-stations based on the position of major foci will probably have to be revised from time to time.

One resolution resulting from the Committee's recommendation dealt with the need for further observations at sea and on outlying oceanic islands. The hope was expressed that means would be found to continue, at least in part, the work of the Carnegie. It was recommended that the need for magnetic work in outlying islands be brought to the attention of various expeditions which might include such work in their programs.

B--Maintenance of the magnetic survey of the United States

This subject is closely related to that just discussed, since the principal problem is maintenance of repeat-observations.

In 1899 the Coast and Geodetic Survey adopted the plan for the magnetic survey of the United States which called for observations at least at every county-seat. This project was practically completed some years ago though for various reasons there are always perhaps a hundred county-seats at which observations have not been made.

With the practical completion of the original plan, except for filling certain gaps, the question as to what should constitute proper maintenance arose. For mapping purposes there is no need for the continued marking of the original stations, except a limited number of repeat-stations. With data from these stations and from magnetic observatories the values at other stations can be brought forward no matter what the date of original observations. However, a program limited to repeat-stations would not be satisfactory for many reasons.

We must remember that the Earth's magnetism came into practical use before its scientific importance was recognized, and it was this practical use which brought about and made possible scientific study. Science cannot fail to recognise this debt. Further, the practical uses have grown and must continue to be met, and some of these uses have called for more scientific knowledge. The principal uses are in the field of navigation of both sea and air, in land-surveying, and in geophysical search for buried geological formation. Many of these uses require that there should be, in addition to repeat-stations, a number of points marked by monuments throughout the country at which at least magnetic declination has been measured.

Of all survey-monuments the magnetic station is the most subject to damage. Aside from the contingencies which may destroy or render useless a station and objects whose true bearing has been determined, there are numerous forms of magnetic and electrical disturbance, by the introduction of magnetic material either above or below ground near the station or the installation of direct-current lines with leakage.

It is recognized that these influences are less in the open country than in the towns and cities, and there is now in progress a gradual substitution of triangulation-stations as magnetic stations. The expansion of the triangulation to all parts of the United States has made this possible.

The practice of placing a convenient azimuth-mark at recent triangulation-stations has resulted in saving of time and effort in determining magnetic declination, since there is no longer need to wait for a clear sky and the azimuth is far better than any obtainable by the magnetic field-party. There has been some difficulty in finding suitable triangulation-stations for magnetic work, since some of these have been placed too near wire-fences or highways with automobiles passing too near, or they have reinforcing iron in the monuments, but most of these faults are being eliminated in the more recent triangulation.

Most of the recent magnetic work has been the reoccupation of repeat-stations and other observations have been supplemental to such work. The change from county-seats to triangulation-stations has been specially important in the case of repeat-stations as the value of a repeat-station lies in long-continued existence without change in magnetic conditions, in which the triangulation-stations would seem to have the advantage. The map of Figure 3 shows the distribution of stations which had been adopted when this change began. It does not show the triangulation-stations already adopted as repeat-stations, as we do not know which are going to survive and no repeat-observations have as yet been made at any of the stations which have been adopted, since in no case has a five-year period elapsed. However, the adopted spacing will not be greatly different.

In changing to the use of triangulation-stations as magnetic repeat-stations, it is necessary to observe at a magnetic station formerly used as a repeat-station as well as at the triangulation-station in the same region selected for future use in order to preserve continuity in our knowledge of the changes. This necessarily adds to the burden of making the change, but in spite of this the change is expected to be worth while.

The continental part of the country is covered every five years, with a ten-year interval for Alaska and for the Philippine Islands. In addition to the repeat-stations it is customary to observe declination at intermediate triangulation-stations at 50-mile intervals.

There are a number of problems. How far should we go in investigating local magnetic disturbance associated with geological formations? How many stations should be placed in the Western mountain regions where improved transportation is making remote regions more accessible? How far should the Government go in providing complete magnetic stations primarily for use in geophysical prospecting? Should magnetic data made available through geological investigation by magnetic methods be incorporated on the magnetic charts, especially in view of the fact that they are often relative and the conversion to absolute values may be uncertain and also that only one element may be observed? The importance of this is that such surveys have been made in areas with large gaps on the existing maps.

In recent years studies have been made of magnetic conditions in several states, using only the results obtained at stations of the United States Coast and Geodetic Survey and representing the anomalies by vectors. These appear to have value but obviously the value would be greatly increased if stations with complete observations were available at more frequent intervals.

A debatable question is whether it is possible in view of local magnetic disturbance to make observations from which line-integrals around an area could be computed to test the non-potential portion of the Earth's field.

An important question is whether the repeat-program should not be modified to use continuously-recording instruments and make observations over at least one full and possibly two days at each station. Should observations in any region be made at two well-marked stations to guard against loss?

All these questions show that there is an intimate relation between the proper maintenance of the field-surveys and scientific utilization of the results.

U. S. Coast and Geodetic Survey,
Washington, D. C.

APPARENT EFFECT OF MAGNETIC ACTIVITY UPON SECULAR VARIATION OF THE VERTICAL COMPONENT OF THE EARTH'S MAGNETIC FIELD

A. G. McNish

In a previous paper (Trans. Amer. Geophys. Union, fourteenth annual meeting, pp. 139-144, 1933) a definite negative correlation was reported between the second differences of the mean annual values of world-wide magnetic activity and magnetic horizontal force at several widely-separated observatories. This correlation demonstrated that during years of high magnetic activity the horizontal force tends to be lower than during inactive years. No correlation was found between the second differences of the horizontal force and the first differences of magnetic activity, indicating that no appreciable carry-over effect of the activity exists.

The explanation which was offered for these phenomena was that the sum of all the post-perturbation depressions, notable in horizontal force during active years, lowers the mean annual values for such years as compared with those for more quiet years. As the characteristic field of a general magnetic storm may, to a first approximation, be considered as a field parallel to the Earth's magnetic axis and directed in the same sense as the internal magnetization of the Earth, a treatment of the vertical-force records, similar to that reported in the earlier paper, should lead to positive correlation-coefficients for the second differences. Certain exceptions, however, are to be expected.

Uncertainties associated with base-line reductions and absolute determinations of vertical force lower the expected correlation. Because the Earth behaves as if its permeability were less than one for fluctuating magnetic fields, the effect of the storms on the annual means of vertical force should be less than on those of horizontal force. This effect is revealed in the average difference of the means for quiet days and disturbed days of each month and year. At all middle-latitude stations the average horizontal force on quiet days is conspicuously higher than on disburbed days while the average vertical force is lower by a smaller amount.

The investigation of the vertical-force records yielded the results shown in Table 1. The correlation-coefficients A of Table 1 are all small, but the chance that they are due to accident alone is slight according to Pearson's tables (K. Pearson, Tables for statisticians and biometricians, 1st Ed., part 2, pp. 185-201, 1931). The coefficients B of Table 1 are so small that they may be considered as accidental. The one outstanding anomaly is the disagreement of the values for Cheltenham with those of the other observatories. It may be noted also that in the investigation of the horizontal-force records, referred to above, Cheltenham appeared anomalous, which fact may be attributed to some local influence in the secular variation at that Observatory.

Table 1--Correlation-coefficients between differences of vertical intensity and of interdiurnal-variability measure of magnetic activity from widely-distributed observatories, (A) second differences and (B) second differences of vertical intensity with first difference of magnetic activity

Observatory	Geomagnetic latitude, °	Dates	A	B
Bombay	9.5 N	1888-1930	+0.17	0.00
Honolulu	21.0 N	1905-1930	+0.13	+0.10
Tucson	40.4 N	1910-1930	+0.17	+0.01
Cheltenham	50.1 N	1903-1930	-0.12	+0.42
Potsdam-Seddin	52.5 N	1893-1928	+0.34	+0.05
Sitka	60.0 N	1905-1930	+0.24	-0.16

The conclusion to be drawn from these results is that during disturbed years the mean value of vertical force is higher than during quiet years, although, after the immediate effect of the activity has passed, the vertical force returns to the value it would have had if no disturbance had occurred. Combining the observed effects on horizontal and vertical force it is concluded that this phenomenon corresponds to an increase in the external field of the Earth during years of high magnetic activity.

Particular interest is attached to the correlation-coefficient between the second differences for Sitka, namely, +0.24. If the explanation of the effect previously given--that it is caused by the addition of all the post-perturbation changes in the elements following storms--were correct, a negative correlation would have been obtained for Sitka because during disturbed days at that Observatory the vertical force is less than during quiet days, contrary to the conditions in lower latitudes. This comparatively large correlation-coefficient, if it is real, is a positive indication that during disturbed years the external magnetic field of the Earth is greater, apart from the immediate effect of magnetic storms. Further results from high-latitude stations are necessary to substantiate this conclusion as the only other observatory of comparably high latitude used in the investigation was Potsdam-Seddin, where middle-latitude conditions obtain. This possibility is further supported by the fact, not brought out in the earlier paper, that the means of the ten least-disturbed days of each month, which are practically free of post-perturbation effects, reveal the same correlation as the means of all days for the observatories at Honolulu, Tucson, Cheltenham, and Sitka. The implications arising from the fact that the Earth has an external field which increases in intensity with the increase of world-wide magnetic activity are too far-reaching to be considered until this variation has been more completely demonstrated.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

AUTO RADIO--AN AID IN GEOLOGIC MAPPING

Ernst Cloos

(Abstract)

Recent experiments have proved that the quality of wireless reception from certain stations is influenced by geologic conditions of the underground. Structural disturbances like faults or steeply dipping rock contacts cause "dead spots." A radio survey of such regions gives valuable indications for the determination of geologic structures on the one hand and may guide the installation of radio sets and transmitting stations on the other.

The paper is to appear in full in the American Journal of Science, 5th ser., v. 28, 1934.

Johns Hopkins University,
Baltimore, Maryland

REPORTS ON MAGNETIC AND ELECTRIC WORK OF ORGANIZATIONS IN NORTH AMERICA DURING 1933-34

Auroral station at the Alaska Agricultural College and School of Mines

The investigation of the aurora has continued during the past year. Simultaneous photographic observations were made whenever possible from two stations for determinations of height and position and a satisfactory number of measurable photographs were secured. In addition, a watch at half-hour intervals has been maintained for the purpose of securing statistical data and to prepare the daily auroral section of the American URSIgram. When aurorae were visible, photographs were made of the display at the local hour. This was done for purposes of record. An attempt was made to do some preliminary spectrographic work; this has not proven satisfactory for several reasons.

Through the generosity of the Carnegie Institution of Washington in supplying funds, the United States Naval Research Laboratory in supplying equipment, and the United States Signal Corps in assigning an operator, continuous measurements of the height of the ionosphere by the reflection-method were maintained at Fairbanks after the close of the International Polar-Year program at the end of August 1933. The equipment was moved from its previous location to College early in February 1934, so that frequent change in frequency could be made more readily. It is hoped that this work can be continued during 1934.

Data on radio reception are taken twice daily when time is received from NAA, Arlington. This, it is believed, would be interesting if compared with magnetic phenomena; however, no correlation has been attempted yet.

Veryl R. Fuller,
College, Alaska, March 17, 1934 Professor, Department of Physics

Magnetic investigations of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, May 1933 to April 1934

Work in the field and at observatories

Magnetic survey and cooperation--The cooperative field-work in China by F. C. Brown of the American Church Mission at Hankow, assisted by C. T. Kwei, was continued. Each observer secured observations at a number of repeat-stations in addition to regular field-observations, and diurnal-variation observations were made at stated intervals throughout the year at Wuchang.

In South America, Ledig completed determinations for standardizing the absolute instruments of the Chilean Polar-Year Station Magallanes. He also assisted in the establishment of the Polar-Year Station there and gave some instruction on the routine of observatory-work. Leaving Magallanes in May 1933, he completed magnetic observations in Argentina and Brazil, and compared his instruments with those of the magnetic observatory at Pilar, Argentina.

During the latter part of April 1934, R. H. Mansfield left the Huancayo Observatory for Buenos Aires and Capetown, Africa. In May he compared his instruments with those used by the University of Capetown at the Polar-Year Observatory. During the remainder of 1934 he is to reoccupy stations along the east coast of Africa and at several inland points, completing his field-work at Suez.

In cooperation with the Hydrographic Office of the United States Navy Department, Lieutenant J. C. Woelfel was instructed in the operation of magnetic instruments, preparatory to survey-operations in Central America from the fall of 1933, during which magnetic secular-variation stations were to be occupied.

Arrangements for the continuation of the cooperation previously effected with the Director of the Meteorological Service of East Africa were continued. E. C. Bullard, of the Department of Geodesy and Geophysics, University of Cambridge, Cambridge, England, was loaned the Department's complete field-outfit by the Meteorological Service to secure observations while engaged in gravimetric work in East Africa.

F. P. Parris and E. M. Shook, of the Department of Historical Research of the Carnegie Institution of Washington, received training in December 1933 in making astronomical observations for the determination of latitude and in observing the magnetic declination preparatory to taking up work in connection with proposed archaeological excavations in Central America.

In accordance with the several resolutions of the International Union of Geodesy and Geophysics at Stockholm and Lisbon, urging,whenever possible, comparison of national magnetic standards, comparisons of magnetic standards of the Carnegie Institution of Washington were made at the Agincourt Observatory of the Canadian Meteorological Service near Toronto and at Cheltenham, Maryland, during September, October, and December 1933, respectively.

Byrd Antarctic Expedition II--In view of the excellent opportunity offered for securing continuous photographic records during at least twelve months at the base-station Little America proposed for the Byrd Antarctic Expedition of 1934-35, cooperative arrangements were made, the Department supplying the necessary equipment including one of the la Cour magnetographs of the International Polar Year Commission. With the cooperation of the United States Coast and Geodetic Survey, Dr. Poulter, who will be in charge of the scientific work of the Expedition, and his assistant were given instruction and training in the use of magnetic absolute and variation instruments. Complete instructions were prepared for the guidance of the observers. It is hoped that besides the observations at the base-station other magnetic stations will be occupied in the course of various sledge-journeys.

International Polar Year 1932-33--Cooperation was continued in the International Polar-Year program. The plans for the establishment of the College-Fairbanks Polar-Year Station were fully realized with the cooperation of the various organizations referred to in last year's report. The magnetic recording with one magnetograph and the earth-current registrations were continued beyond the end of the Polar Year, until May 1933.

The special radio observations for the determination of the ionization of the Kennelly-Heaviside layer in accordance with the Polar-Year program were realized for a part of the Polar Year at the Huancayo Magnetic Observatory. Some work in the determination of the heights of the Kennelly-Heaviside layer was also done at the College-Fairbanks Station. Rapid-running la Cour magnetographs were operated at the Huancayo and Watheroo magnetic observatories.

Observatories--The cooperation with the Apia Observatory, Western Samoa, was continued.

The usual schedules of observations in terrestrial magnetism and electricity have been continued at Watheroo and Huancayo observatories. By use of a Helmholtz coil, rigid control was exercised over the vertical-intensity variometers at both observatories by frequent determinations of the scale-values. Excellent results have been obtained with the Hale spectrohelioscope at the Watheroo Observatory.

Laboratory investigations

Ionospheric investigations--The idea that the cause of the diurnal variation and disturbances of the Earth's magnetism is largely to be sought in the upper regions of the Earth's atmosphere is not new but heretofore only indirect and inadequate means have been available for this study. A powerful aid for such research is now furnished by modern developments of radio methods. With a detailed knowledge of the numerical values of the ionization of the ionized strata and their changes with time, values which can only be obtained by advanced radio methods, together with information from other sources, it should be possible to reach decisions regarding the validity of existing theories and to make extensions which will provide more adequately for the quantitative and qualitative requirements. L. V. Berkner has been engaged in developing equipment and methods for automatic registration of full ranges of heights and corresponding values of ionization of the ionosphere and in devising a systematic tabulation of information of the ionosphere-records and analyses of these data.

The investigations at the Huancayo Magnetic Observatory during 1933 on the electrical structure of the upper atmosphere above 100 km--the ionosphere--constitute the first of their kind obtained at a station near the geographical equator and practically on the magnetic equator. These show the presence there also of the three important strata (lower E-layer, intermediate daylight F-layer, and upper F_2-layer) of the ionosphere, which have been observed at stations in the temperate zones, thus indicating substantially their world-wide character, and yield values for the numbers of electrons per unit-volume in each of these three layers. The Earth's magnetic field causes the exploring radio wave to be split into two components. These two rays are returned from the same height at different frequencies and these observed frequencies at Huancayo agree with values predicted from Breit's theoretical considerations published in 1927. Because of the small magnetic field at Huancayo, this agreement would not exist if ions rather than lighter electrons predominated. It shows that the numbers of ions in the intermediate layer can not exceed 10^7 per cc, a value a hundred-fold lower than the limit previously set. The results further show that the intermediate (daytime) layer is formed by a gradual separation of the upper region into two parts rather than by distinctly new ionization and that the upper layer is a region of rich ionization of considerable vertical extent. These facts have a direct bearing on theories of diurnal variation of terrestrial magnetism and further demonstrate the value in terrestrial-magnetic research of investigations of the upper atmosphere by radio methods.

Ionization-measurements during thunder-storms--The rate of ionization inside a thin-walled chamber has been recorded by G. R. Wait and A. G. McNish on the grounds of the Department during the past year. A large definite diurnal-variation in the rate of ionization was found. Moreover, the ionization was found to increase several fold at the time of thunder-storms. The increase in ionization usually has an abrupt beginning, coinciding with the beginning of the rain. The total amount of increase is roughly proportional to the total amount of rainfall. The ionization begins to decrease as soon as the rain ceases, the decrease with time being of such a character as to be explainable by assuming that decay-products of radium, principally radium B and radium C in equilibrium with it, are carried to the Earth's surface by the rain.

Intermediate and small ions--Wait and Torreson have completed an investigation extending over a portion of two months on the effect that intermediate ions have on small-ion measurements. This investigation has led to the formulation of a new theory regarding the character and mode of formulation of the intermediate ions which play an important rôle in atmospheric phenomena.

Diurnal variation in the rate of ionization near the Earth's surface--Contrary to the expectation, there has been found a distinct and systematic daily variation in the rate of ionization near the ground. It is possible to account for this observed variation on the assumption that convection-currents during the warmer part of the day carry radioactive materials away from the Earth's surface, thus diminishing the rate of ionization due to this source near the ground. This variation during the summer was found to be as much as 30 to 40 per cent and hence has an important bearing on atmospheric-electric studies. Correcting for the presence of intermediate ions, it has been possible to check more accurately the theories of small-ion formation and removal in the atmosphere.

Nuclear physics--The extension of the Experiment Building to house a large generator for high voltage was completed by the end of July 1933. In the meantime, the reconstruction of the 2-meter Van de Graaff electrostatic generator had been under way so that its installation in the new building could be begun in August, after which several months were consumed in setting up and adjusting the observational apparatus for experiments with protons and deutons.

From the experimental work thus far conducted, two major results have already emerged: (1) The identification of the contamination responsible for most of the disintegration-effects thus far observed using deutons, and (2) the new evidence for hydrogen of mass three.

(1) The atoms which give rise to pseudo-transmutations of carbon, oxygen, and other targets when bombarded by high-speed atoms of heavy hydrogen are found to be the atoms of heavy hydrogen itself occluded in the pores of the solid targets, after being driven there by the high-speed beam. Thus the collision of one heavy hydrogen atom

against another, when the first one is moving at the tremendous speed produced by a vacuum-tube operated at more than one million volts, causes an atomic transmutation and as one result a new-born atom of ordinary hydrogen is ejected with an energy of more than two million volts.

Finding that their results on atomic disintegration of six selected targets were inconsistent with those announced from other laboratories, and that their own results changed from time to time, Tuve, Hafstad, and Dahl decided that some elusive contamination was responsible for the apparent disintegrations observed with their solid carbon and quartz targets. Devising a special arrangement for bombarding pure gases which could be pumped through the exposure-chamber to prevent the accumulation of unknown contaminations, they first found that the chemical elements carbon, oxygen, nitrogen, and ordinary hydrogen gave no signs of disintegration. But on introducing into the chamber a sample of heavy hydrogen, they instantly recorded enormous numbers of disintegration-particles identical with those which had been disturbing investigators working in this field during the past year.

(2) New evidence for the existence of hydrogen atoms of mass three has been found as a by-product of the investigation. These new observations were made using a specially purified sample of deuterium gas prepared by Dr. Urey of Columbia University. Only extremely small amounts of the hydrogen isotope of mass three are indicated. The measurements show only one part of triple-weight hydrogen in 10,000 million parts of ordinary hydrogen, or about one part in one million of the concentrated sample of heavy hydrogen. The method used, however, is amply sensitive to detect such small quantities, since the high-voltage technique makes it possible to detect even single atoms. (This evidence, although repeatedly obtained, is from only one type of experiment, and hence it is felt that as yet it does not constitute final proof of the existence of stable mass-three hydrogen atoms.)

Compilation and discussion of terrestrial-magnetic data

Compilation of observatory-data--Before publication there is being added to the tabulation of the magnetic data from records at the Watheroo Magnetic Observatory during 1919-30 those for the years 1931 and 1932. Good progress is being made on similar data obtained at the Huancayo Magnetic Observatory during 1922 to 1932; these will constitute a second volume of results.

The investigation of the secular-variation data and isoporic changes in the Pacific Ocean, as initiated by Fisk, based on all the observations of the Galilee and Carnegie from 1905 to 1929, is in progress by Duvall. The least-square reductions for declination are nearly completed. It is planned that these will be followed by like compilations for horizontal intensity and inclination.

The final reduction of the magnetic observations obtained by the MacMillan expeditions to Baffin Island and to northern Greenland and by the First Byrd Antarctic Expedition is nearing completion by Wallis and Ennis.

The earth-current results obtained at the College-Fairbanks Polar-Year Station of 1932-33 have been completely reduced by Rooney, and a detailed comparison of earth-current disturbances and auroral displays has been prepared. The reduction of the records of atmospheric potential-gradient and conductivity is well under way by Sherman.

Investigation of sudden commencements--Study of sudden-commencement and mean disturbance vectors for Watheroo in general reveals a tendency toward parallelism with the Earth's magnetic axis. The difference between means of the quiet and disturbed days is diametrically opposed to the sudden-commencement vector. Sudden commencements were found to exhibit a preference for certain hours of the day and certain seasons of the year. The average number of yearly occurrences closely parallels the magnetic activity.

Theory of the H-variometer--S. E. Forbush has been engaged on an investigation of the theory of the H-variometer with a view to the unification of procedure at observatories.

Diurnal variation--The determination and analysis of the lunar magnetic variations from data from the Watheroo and Huancayo magnetic observatories by Bartels is being continued.

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J. A. Fleming,
Washington, D. C., April 26, 1934 Acting Director

Geophysical work of the United States Bureau of Mines

Preliminary work was done upon apparatus and equipment for measuring vibrations of ground caused by blasting in quarries; devices are now ready for field-service. Inasmuch as the results of blasting in the vicinity of privately owned property often lead to litigation, it was necessary to establish instruments of measurement more precise than those now available. It was also necessary to design proper master vibration-producing apparatus for checking the field-instruments. In this connection, the work done by Anderson and Wood of the Carnegie Institution of Washington upon the theory of such instruments was checked. It was found that their analysis of a simple transient-vibration was inadequate, as the matter is complicated by a large number of impulses separated at short time-intervals.

Some preliminary apparatus has been made to measure the air-wave or concussion-wave which results from some blasting operations. Heretofore, only qualitative tests have been customary, and measurements of absolute values are more desirable. However, due to a lack of funds, it is impossible to proceed with these projects.

Construction of a simple field-apparatus was commenced for exploring radioactive districts using the principle of the Geiger counter. It was thought advisable to make a comparison with the radon-content of the air in the soil and the gamma-rays in the region. If a close comparison exists between these two factors, radioactivity explorations can be speeded up about five to six times, as it would be unnecessary to draw samples of air diffused in the ground for making these measurements.

A resistivity-survey was made at the Grand Coulee damsite on the Columbia River to determine the subsurface topography of the bed-rock. The results have since been corroborated by diamond drilling.

Magnetometer-surveys were made upon some iron-ore deposits in Puerto Rico to indicate their extent and outline.

Scott Turner,
Washington, D. C., March 25, 1934 Director

Magnetic work of the United States Coast and Geodetic Survey, April 1933 to March 1934

Magnetic surveys--Occupation of repeat-stations for determination of the secular change of the Earth's magnetism has continued the principal feature of the field-work in terrestrial magnetism. The rule has been to make complete observations on two days at each station selected for future reoccupation. As a secondary feature, declination-observations have been made along the route of travel between the repeat-stations, at intervals of 50 miles, for the benefit of local surveyors. Triangulation-stations have been used as magnetic stations wherever suitable ones are available. The work during April 1933 to March 1934 covered the states of Oklahoma, Texas, New Mexico, Arizona, Colorado, Wyoming, Nebraska, Washington, Oregon, and California.

Declination-observations with compass-declinometer have been made in connection with the hydrographic and topographic surveys in Alaska and the Philippine Islands. Some results for declination at old stations have been made by local surveyors working under State allotments from the Civil Works Administration, furnishing additional control on the secular change.

Magnetic observatories--The five regular magnetic observatories have operated continuously. Preparations have been made for installing at Cheltenham, Sitka, and Tucson a set of insensitive la Cour variometers, provided the instruments become available, in order to insure a complete record even at the time of the most severe magnetic storms.

On inspection of the variation-building at Cheltenham, Maryland, it was found that termites had done considerable damage to the heavy timbers of the underpinning. These timbers are being replaced by walls of concrete and precautions are being taken to prevent the termites from extending their ravages to the upper part of the building. While the repairs are in progress a set of la Cour variometers is being operated in the comparison-and-test building to guard against loss of record.

The absolute- and variation-buildings at San Juan, Puerto Rico, have been encased in concrete as a protection from damage by hurricane, resulting in improved operating conditions. The vertical-intensity variometer has been compensated for temperature.

At Tucson, Arizona, it has been possible to continue the photographic record of conductivity, potential gradient, and earth-currents, thanks to the cooperation of the Carnegie Institution of Washington, the American Telephone and Telegraph Company, and the Mountain States Telephone and Telegraph Company. Up to the end of 1933, this Observatory continued to furnish reports of magnetic character of days for the daily radio broadcast of cosmic data sent out under the auspices of Science Service. Beginning with January 1, 1934, this duty was transferred to the Cheltenham Observatory.

College-Fairbanks Polar-Year Station--The full Polar-Year program was concluded at the end of August 1933. Upon the strong recommendation of the International Polar-Year Commission, arrangements were made to continue the operation of the insensitive set of la Cour variometers and the earth-current recorder until March 31, 1934. The computation of the results of the Polar-Year work is in progress.

Publications--To meet the needs of local surveyors and engineers, publications in mimeograph form have been issued under the titles "Magnetic Declination in South Carolina" and "Magnetic Declination in Louisiana." Lack of funds prevented the issue of other publications. The computation of the observatory-records is steadily progressing and the results for the four years 1927-30 are now nearly ready for publication.

Reports of magnetic character of days and of magnetic activity for the five magnetic observatories have been forwarded regularly to the International Commission for Terrestrial Magnetism and Atmospheric Electricity.

Use of the results of the observatory-records is steadily increasing, particularly in connection with studies of radio transmission. A questionnaire was sent recently to persons and organizations on the mailing list in order to determine to what extent the observatory-publications are actually used and whether a less detailed publication would meet existing needs. Replies were received from twenty-five countries. Of these 70 per cent, including at least one from each country, indicated a general demand for the complete publications on the part of those making use of them.

R. S. Patton,
Director

Washington, D. C., March 28, 1934

Magnetic observations in the northern states of Mexico during 1933

During the year 1933 the Magnetic Section of this Astronomical Observatory of Mexico made observations of absolute magnetic values at some places in the northern states of Mexico. This work was valuable because of the results obtained and also because of the comparisons between our instrument (C.I.W. type) and those of the Tucson Magnetic Observatory belonging to the United States Coast and Geodetic Survey. The results of this comparison of standards are given in Table 1.

Rosendo O. Sandoval was in charge of the Expedition and he made the comparisons with R. G. Ambrose of the United States Coast and Geodetic Survey. The results are given in Table 2.

I beg to note the discrepancy between the declination-values observed at El Paso, Texas, and Ciudad Juárez, Chihuahua, by Messrs. Ambrose and Sandoval; the difference reaches 38'. As our computations seem to be correct, Mr. Sandoval thinks that there may be a local disturbance near the stations.

In 1906 and 1924, the observers of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington found a local disturbance at the eastern and southern parts of Chihuahua City, the same as that found by Mr. Sandoval in 1923 at the southern part of the City, but not at the west, in front of Nombre de Dios in 1923, nor between the river and the airport in 1933.

The standard absolute instruments at the Tucson Magnetic Observatory were Coast and Geodetic Survey theodolite-magnetometer No. 30 and earth inductor Schulze No. 63. The instrument used by Mr. Sandoval was magnetometer-inductor No. 107 of C.I.W. type manufactured by the Precise Instrument Company of Brooklyn, New York.

Table 1--Results of comparison of magnetic instruments at Tucson Observatory

Date	Element	Instruments		Tucson - Tacubaya
		Tacubaya	Tucson	
1933		° '	° '	'
July 19	D	+13 50.0	+13 50.3	+0.3
19		+13 44.5	+13 45.2	+0.7
20		+13 53.9	+13 53.6	-0.3
20		+13 49.9	+13 50.4	+0.5
July 19	I	+59 41.4	+59 39.4	-2.0
19		+59 41.6	+59 40.1	-1.5
20		+59 43.2	+59 41.0	-2.2
		γ	γ	γ
July 19	Z	26363	26320	-43
20		26382	26342	-40

Table 2--Results of magnetic observations in the northern states of Mexico during 1933

Station	Latitude north	Longitude west	Dates	East decl'n D	North incl'n I	Horizontal intensity H
	° '	° '	1933	° '	° '	γ
Chihuahua						
Jiménez	+27 07.7	104 56	July 21,22	11 35.6	55 04.1	28456
Chihuahua	28 38.3	106 05	15,16,17	11 48.5	56 14.8	28238
Ojinaga	29 33.9	104 25	19	11 58.3	57 56.8	27376
Nueva Casas Grandes	30 25.5	107 55	11,12	13 11.7	57 34.7	27550
Ciudad Juárez	31 43.8	106 29	6, 7, 8	13 14.6	59 53.1	26476
Coahuila						
Saltillo	25 26.1	101 00	June 7, 8	10 10.7	54 02.3	28942
Piedras Negras	28 42.8	100 31	14,15	10 37.6	57 53.4	27423
Nuevo Leon						
Monterrey	25 40.1	100 18	June 4, 5	10 17.3	54 29.7	28778
Sonora						
Navojoa	27 34.1	109 27	June 30,July 1	12 27.5	54 18.6	28642
Guaymas	27 55.9	110 58	27,28	12 44.8	54 56.2	28428
Hermosillo	29 04.5	110 58	25,26	12 33.7	55 54.9	27959
Nogales	31 17.2	110 57	22,23	13 49.5	58 21.5	26954
Tamaulipas						
Tampico	22 13.0	97 52	May 29,30	9 17.9	51 07.9	30105
Ciudad Victoria	23 45.6	99 08	June 1, 2	9 53.6	52 23.2	29600
Nuevo Laredo	27 30.8	99 30	10,11	10 05.8	56 54.6	27814
Texas*						
Laredo	27 30	99 31	June 5, 7	10 25.2	56 46.8	27707
El Paso	31 48	106 26	May 15,16	12 36.8	59 58.9	26300
Arizona	31 21	110 56	24,25	13 49.3	58 24.0	26962

*Observations in Texas were made by R. G. Ambrose, of the U.S. Coast and Geodetic Survey.

Joaquin Gallo, Director,
Observatorio Astronómico Nacional de Mexico

Tacubaya, D.F., Mexico, March 12, 1934

Researches at Mount Wilson Observatory of the Carnegie Institution of Washington relating to terrestrial magnetism

Continuous records of horizontal intensity and declination have been continued at Mount Wilson. The magnetic character-figures estimated from these records and the character-figures representing solar activity have been published regularly in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

Both solar and magnetic activity have been near minimum during the past year. The exact time of neither minimum can be determined until some time after it has been passed, but the minimum of the solar cycle as determined by the sunspots can be estimated better than that of terrestrial magnetism. Near the time of sunspot-minimum, spots belonging to the waning cycle lie near the solar equator and those of the new cycle about 30° from it. The magnetic fields in the sunspots belonging to the two cycles are of opposite polarity and so it is possible to tell definitely when the new cycle begins. The time of minimum occurs before the new cycle has developed much activity but while spots of the old cycle are still occurring.

Five groups of spots belonging to the new cycle have been observed up to March 19, 1934, the first in October 1933. The time of minimum has been estimated as December 1933, but this date must be considered as provisional until the new cycle is further developed.

Seth B. Nicholson

Pasadena, California, March 20, 1934

Large electrical map of Central Massachusetts by the Massachusetts Institute of Technology

A large electrical map of a region about 60 miles in diameter was recently completed in central Massachusetts. Commutated direct-currents of 10 to 25 amperes (maximum voltage, 280) were passed between two grounds separated 60 km, one being at West Roxbury (Greater Boston) and the other at Clinton, Massachusetts. A transmission-line kindly provided by the New England Power Association and the Edison Electric Illuminating Company of Boston was used to connect these points. The resulting electrical potentials were measured by potentiometer-methods at 92 points in the area, by the use of telephone-circuits kindly furnished by the New England Telephone Company. The most distant observation was at Pittsfield, Massachusetts--a distance of about 135 km from the source electrode.

Numerous oscillograph-records were made. The influence of frequency of commutation, current-density, and the problem of reducing interfering potentials induced by natural and artificial causes were studied. It appears that maps of this size can be made with fair accuracy. The criterion for the estimation of accuracy was the closure-error involved in measuring potentials between pairs of points along different paths. As an example, the best test obtained on closures involved the voltage-drop between Clinton and Gardiner, a distance of 30 km. This was measured along six different paths, and yielded, after a least-square adjustment, the following drops: 2.802, 2.804, 2.805, 2.805, 2.805, 2.806 volts. This test represents the best results obtained, and the agreement is so good that it must be to some extent fortuitous. The chief experimental problem in this type of work is clearly that of reducing the influence of those components of the extraneous electromotive forces which fluctuate markedly at periods of the order of the commutation, that is, with periods between 1/5 and 10 seconds (the commutation-interval was about one second, as a rule). Fluctuations with other periods cause relatively little difficulty.

According to recent theoretical results, it is possible to determine directly the variation of the electrical resistivity with depth, in a symmetrical earth, from such maps. It is hoped to continue the work in areas especially selected for this purpose.

L. B. Slichter, Professor of Geophysics,
Boston, Massachusetts, April 16, 1934 Massachusetts Institute of Technology

Researches related to terrestrial magnetism and electricity of the United States Naval Research Laboratory

In September 1933, H. B. Maris completed a year's work at the Polar-Year Station at Fairbanks, Alaska, on investigations of the ionosphere and spectra of the arctic sky. By means of the radio echo-method of Breit and Tuve using 73-meter waves, the apparent heights of the E-layer were observed to be around 130 km and of the F-layer from 180 to 300 km and more. As in temperate latitudes, the echoes from the ionosphere were often obliterated during strong magnetic disturbance and increased in intensity during mild magnetic disturbance. Echoes during zenith auroral displays were often reduced in intensity as if by absorption but exhibited no marked changes in ionosphere-heights.

Spectra of the light of the twilight-sky when the sky was very clear showed the presence of radiations in the yellow and red different from scattered sunlight which probably originate in the upper atmosphere. The radiation varied greatly in intensity and somewhat in character from full daylight to complete night-light.

The short-wave limit of ultraviolet spectra of the daylight sky varied with the altitude of the Sun. Qualitatively, the variations indicated that the thickness of the ozone in the high atmosphere above Fairbanks was pretty much the same as that in temperate latitudes.

H. R. Greenlee, Captain, U.S.N.,
Washington, D. C., April 4, 1934 Director

Research in atmospheric electricity at Stanford University

A second year of continuous recording of space-charge at two elevations has been completed and mean curves of the diurnal variation for each month have been computed. The effect of turbulence as the chief factor in determining the variation has been fully confirmed. Russell Nielsen has begun taking continuous records of dust-content of the air and hopes soon to have enough data from which to warrant some inferences concerning the effect of dust upon the space-charge and gradient. Recording of the gradient at the surface has also been continued, and five-year mean curves for the diurnal variation are now available.

Philip D. Williams is working on a continuous recording outfit for air-earth currents. Plans are under way for developing portable outfits for making space-charge and gradient measurements in the free air at moderate elevations. It is hoped that this equipment can be used in small dirigibles or on captive balloons for obtaining values in the air up to one or two kilometers, particularly through the temperature-inversion layer. Values in this region have been inferred but not measured. This work will be made possible through the cooperation of the Naval Air Base at Sunnyvale.

J. G. Brown,
Stanford University, March 26, 1934 Professor of Physics

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF OCEANOGRAPHY

Washington, D. C.
April 27, 1934

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THE OCEANOGRAPHIC ACTIVITIES OF THE HYDROGRAPHIC OFFICE AND THE UNITED STATES NAVY DURING APRIL 1933 TO APRIL 1934

W. R. Gherardi

During the year April 1933 to April 1934 the oceanographic activities of the Hydrographic Office and the United States Navy were more varied and related to areas more widely separated than during recent former years. They are briefly summarized below.

United States Naval surveys--Working under the direction and guidance of the Hydrographic Office two surveying-vessels, the U.S.S. Hannibal and the U.S.S. Nokomis, conducted surveys in the Gulf of Panama and Panaman and Costa Rican waters gathering timely information regarding those waters for the further safety of navigation. Those vessels completed the hydrographic survey of the Gulf of Panama during the season of 1933, and are developing the area west of the Gulf of Panama between Morro Puercos and Burica Point, the latter on the boundary between Panama and Costa Rica.

The U.S.S. Argonne and the U.S.S. Gannet, assisted by several other United States Naval vessels, conducted surveys among some of the Aleutian Islands.

Aerial photography was employed in connection with all the surveys for detailed delineation of shore-lines and other topographic features.

The main triangulation of the Gulf of Panama survey was carried across country by the survey party of the Hannibal from Parita Bay to Montijo Bay with the object of connecting, in the vicinity of Coiba Island, with the Nokomis triangulation as expanded eastward from a measured base in the Parida Island Area. It is expected to have, before the end of the survey-season of 1934, a continuous chain of triangulation extending from Parita Bay in the Gulf of Panama to Charco Azul Bay (Fig. 1).

Approximately 50 per cent of the hydrography within the area covered by the attached chartlet will be developed during the present survey-season.

An aerial photographic party photographed, with a five-lens camera, the coastline of Panama and Costa Rica from Mariato Point in Panama to Judas Point, Costa Rica.

Two precise astronomical determinations of geographic positions have been made

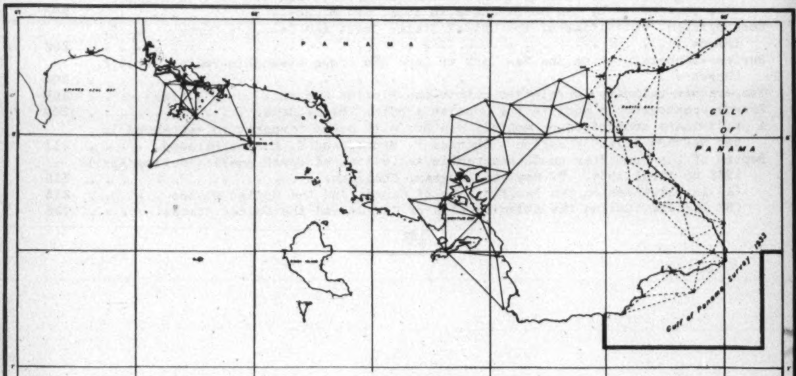


Figure 1

this year, one at Puerto Armuelles, Panama, the other at Puntarenas, Costa Rica.

Charts from United States Naval surveys--Ten new Hydrographic Office charts have been published in the year 1933 based upon original United States Naval surveys. They are: No. 1410, Bahia San Miguel, Gulf of Panama; No. 1963, South entrance to Gulf of Paria, Serpents Mouth; No. 1964, Bocas del Dragon, North entrance to Gulf of Paria; No. 5584, Panama Canal to Bahia San Miguel including Archipielago de las Perlas; No. 5588, Harbors in the Gulf of Paria, Venezuela, including Ensenada Cariaquita, Ensenada Patao, Ensenada Ucarito, Puerto Cristobal Colon (Macura), Ensenada Guinimita, and Ensenada Yacua; No. 5589, Rio Grande and Approaches, Venezuela; No. 5168, Ports on the north coast of Cuba including Puerto Cayo Moa, Puerto Cebollas, Puerto Cananova, and Puerto Yaguaneque; No. 1862, Bahia Banes, Cuba; No. 2630, Cayo Moa Grande to Cape Maysi, north coast of Cuba; No. 5169, Ports on the north coast of Cuba including Bahia do Taco, Ensenada Jaragua, Puerto Mata, Puerto Boma, Puerto Maravi, Puerto Cayaguaneque, Puerto Naias, Puerto Baracoa, and Puerto Bahia Miel.

Sonic soundings obtained by United States Naval vessels--The following is a tabulated list of sonic soundings taken by United States Naval vessels from January 1932 to December 31, 1933:

U.S.S. *Nokomis* - Recorded 361 sonic soundings enroute Guantanamo Bay, Cuba, to Coco Solo, Canal Zone, crossing 10° 16' N in 79° 22' W and 9° 48' N in 79° 43' 45" W, and enroute Iguana Island, Panama, to Balboa, Canal Zone, to Perlas Islands, Jicarita Island, and Cape Mala, Panama, crossing 7° 36' 30" N in 79° 57' 45" W, and 8° 49' N in 79° 29' 03" W.

U.S.S. *Hannibal* - 23 sonic soundings off Coiba Island, Panama, crossing 7° 12' 55" N in 81° 52' 30" W, and 7° 10' 45" N in 81° 09' W.

U.S.S. *Ramapo* - Enroute San Pedro, California, to Guam, Mariana Islands, and Manila, Philippine Islands, obtained a line of 353 sonic soundings crossing 21° 00' N in 160° 35' 30" W, 20° 16' N in 178° 52' 30" W, and 13° 06' N in 131° 10' E.

U.S.S. *Nokomis* - Line of 55 sonic soundings taken enroute Villa Island to Perlas Islands, Panama, crossing 8° 04' 32" N in 79° 55' 03" W, and 7° 37' 16" N in 79° 52' 36" W.

U.S.S. *Indianapolis* - Line of 84 fathometer-soundings taken through the Crooked Island Passage, crossing 23° N and 74° 30' W.

U.S.S. *Indianapolis* - Line of 35 fathometer-soundings taken off Pedernales Point, Ecuador, crossing 0° N in 80° 12' W and 5° N in 80° 12' W.

U.S.S. *Altair* and *Arizona* - 45 sonic soundings taken in San Pedro, California, to San Diego, California (area, subsequent to the earthquake of March 10, 1933), crossing 32° N in 117° W and 32° 40' N in 118° W.

U.S.S. *Lexington* - 65 sonic soundings taken enroute San Francisco, California, to Hawaii, crossing 33° 20' N in 120° 15' W and 22° N in 157° W, and return trip crossing 13° N in 157° 45' W and 28° 45' N in 140° W.

U.S.S. *Indianapolis* - Line of 25 fathometer-soundings taken northwest of Chincah Island Light crossing 13° 10' S in 76° 20' W and 13° 40' S in 76° 50' W.

U.S.S. *Indianapolis* - Line of 26 fathometer-soundings taken in vicinity of Galera Point, Ecuador, crossing 2° 00' N in 80° 15' W and 7° 00' N in 79° 45' W.

U.S.S. *Altair*, *Dobbin*, and *Whitney* - 544 fathometer-soundings taken in San Pedro to San Diego (California) Area, crossing 32° 20' N in 117° 30' W.

U.S.S. *Indianapolis* - A line of 35 fathometer-soundings obtained west of Mariguana Island in 21° 50' N in 73° 20' W and 23° N in 73° 15' W.

U.S.S. *Vega* - Obtained 45 fathometer-soundings off Santa Margarita Island, Lower California, crossing 24° 30' N in 112° 10' W.

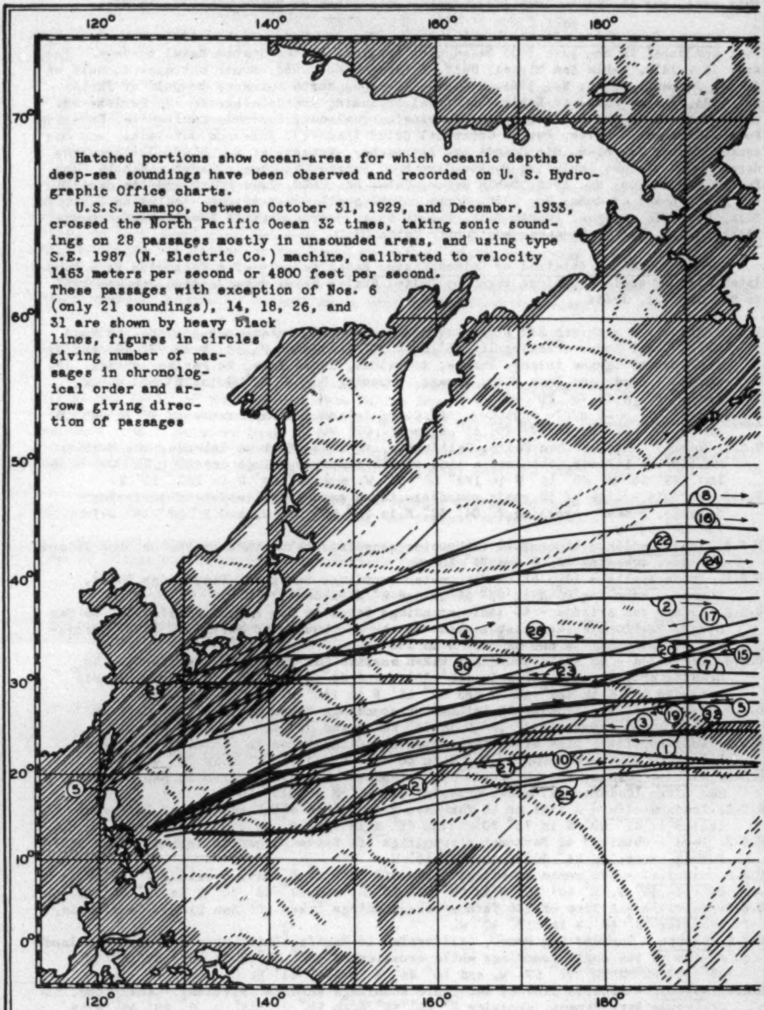
U.S.S. *Hannibal* - 106 sonic soundings taken off Gulf of Panama, crossing 7° 25' N in 82° 11' 40" W, 9° 40' 30" N in 79° 50' 05" W, and 11° 56' 30" N in 79° 05' 45" W.

U.S.S. *Melville* - A line of 135 fathometer-soundings taken off San Diego, California, crossing 32° 40' N in 117° 40' W.

U.S.S. *Ramapo* - Enroute San Pedro, California, to Manila, Philippine Islands, obtained a line of 355 sonic soundings while crossing 22° 32' 30" N in 157° 56' 30" W, 22° 35' 30" N in 177° 59' W, and 16° 24' N in 134° 31' E.

U.S.S. *Nokomis* - Records line of 245 sonic soundings enroute Cristobal, Canal Zone, to Almirante Bay, Panama, crossing 9° 23' 45" N in 79° 57' 29" W, 9° 28' 45" N in 82° 11' 45" W, and 9° 17' 20" N in 81° 50' W.

U.S.S. *Ramapo* - Line of 365 sonic soundings taken enroute Manila, Philippine Islands, to San Diego, California, crossing 24° 08' 30" N in 132° 25' 30" E, 34° 30' N in 163° 03' E, and 34° 52' N in 155° 27' W.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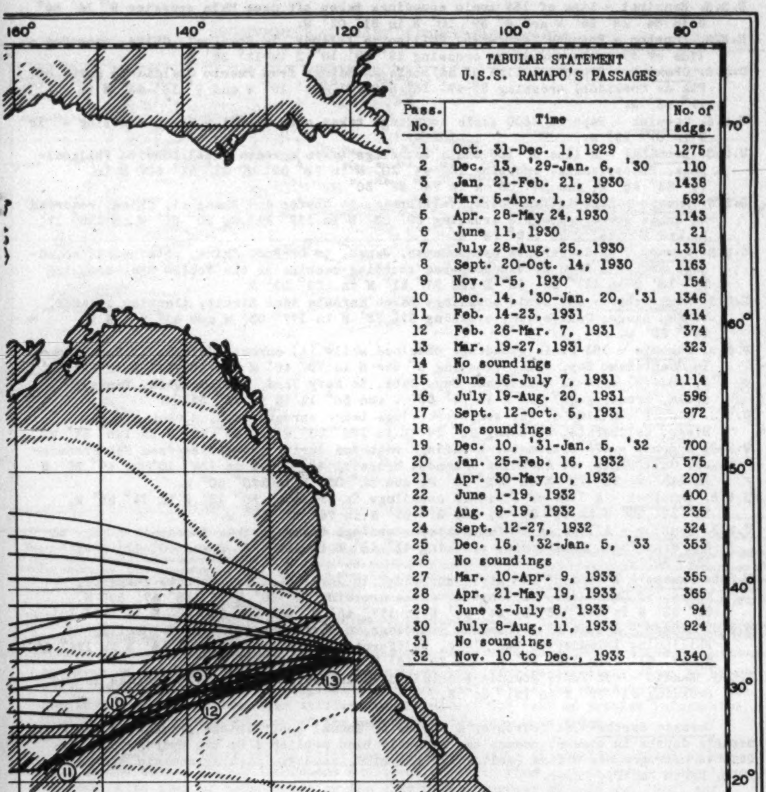
25
5

Hatched portions show ocean-areas for which oceanic depths or deep-sea soundings have been observed and recorded on U. S. Hydrographic Office charts.

U.S.S. Ramapo, between October 31, 1929, and December, 1933, crossed the North Pacific Ocean 32 times, taking sonic soundings on 28 passages mostly in unsounded areas, and using type S.E. 1987 (N. Electric Co.) machine, calibrated to velocity 1463 meters per second or 4800 feet per second. These passages with exception of Nos. 6 (only 21 soundings), 14, 18, 26, and 31 are shown by heavy black lines, figures in circles giving number of passages in chronological order and arrows giving direction of passages

FIGURE NO. 2—INDEX-CHART OF



TABULAR STATEMENT
U.S.S. RAMAPO'S PASSAGES

Pass. No.	Time	No. of sdgs.
1	Oct. 31-Dec. 1, 1929	1275
2	Dec. 13, '29-Jan. 6, '30	110
3	Jan. 21-Feb. 21, 1930	1438
4	Mar. 5-Apr. 1, 1930	592
5	Apr. 28-May 24, 1930	1143
6	June 11, 1930	21
7	July 28-Aug. 25, 1930	1315
8	Sept. 20-Oct. 14, 1930	1163
9	Nov. 1-5, 1930	154
10	Dec. 14, '30-Jan. 20, '31	1346
11	Feb. 14-23, 1931	414
12	Feb. 26-Mar. 7, 1931	374
13	Mar. 19-27, 1931	323
14	No soundings	
15	June 16-July 7, 1931	1114
16	July 19-Aug. 20, 1931	596
17	Sept. 12-Oct. 5, 1931	972
18	No soundings	
19	Dec. 10, '31-Jan. 5, '32	700
20	Jan. 25-Feb. 16, 1932	575
21	Apr. 30-May 10, 1932	207
22	June 1-19, 1932	400
23	Aug. 9-19, 1932	235
24	Sept. 12-27, 1932	324
25	Dec. 16, '32-Jan. 5, '33	353
26	No soundings	
27	Mar. 10-Apr. 9, 1933	355
28	Apr. 21-May 19, 1933	365
29	June 3-July 8, 1933	94
30	July 8-Aug. 11, 1933	924
31	No soundings	
32	Nov. 10 to Dec., 1933	1340

UNSOUNDED AREAS, NORTH PACIFIC OCEAN

U.S.S. *Hannibal* - Line of 189 sonic soundings taken off Cape Mala crossing 9° 14' 44" N in 84° 28' 35" W and 6° 59' 10" N in 81° 02' W.

U.S.S. *Houston* - Enroute Zamboango, Philippine Islands, to Shanghai, China, recorded a line of 42 sonic soundings crossing 19° 59' 10" N in 12° 32' E.

U.S.S. *Chewink* - Reports a line of 54 sonic soundings from Puerto Obaldia to north of Pta de Moskidos, crossing 8° 47' 18" N in 77° 24' 19" W and 9° 16' 43" N in 77° 46' W.

U.S.S. *Chewink* - Reports 2400 sonic soundings taken over Guardian Bank, crossing 9° 15' N in 87° 15' W.

U.S.S. *Hannibal* - A line of 100 sonic soundings taken enroute Canal Zone to Philadelphia, Pennsylvania, crossing 10° 44' 20" N in 79° 09' W, 22° 22' 50" N in 74° 23' 45" W, and 30° 00' N in 74° 52' 30" W.

U.S.S. *Ramapo* - Enroute San Pedro, California, to Chefoo and Shanghai, China, recorded 94 sonic soundings while crossing 30° 03' N in 139° 41' E, 30° 01' N in 135° 17' E, and 30° 44' N in 129° 23' E.

U.S.S. *Ramapo* - While enroute Osumi Gunto, Japan, to Chefoo, China, obtained 42 soundings with the Lord Kelvin deep-sea sounding-machine in the Yellow Sea, crossing 32° 16' N in 127° 25' 35" E and 37° 21' N in 123° 00' E.

U.S.S. *Kingfisher* - 125 sonic soundings taken enroute Adak Strait, Aleutian Islands, to San Diego, California, crossing 51° 32' N in 177° 03' W and 43° 58' N in 147° 20' W.

U.S.S. *Nokomis* - 163 sonic soundings obtained while (A) enroute Cristobal, Canal Zone, to Guantanamo Bay, Cuba, crossing 9° 35' N in 79° 45' W and 18° 17' N in 74° 44' W, and (B) enroute Guantanamo Bay, Cuba, to Navy Yard, Philadelphia, Pennsylvania, crossing 20° 15' N in 74° 03' W and 36° 11' N in 74° 33' W.

U.S.S. *Gannet* - A line of 241 sonic soundings taken enroute Adak, Alaska, to San Diego, California, crossing 51° 29' N in 176° 20' W and 43° 10' N in 135° 54' W.

U.S.S. *Argonne* - 279 fathometer-soundings recorded during the cruise from San Francisco, California, to Aleutian Islands, crossing 38° 40' N in 124° 10' W, 49° 30' N in 145° W, 53° 20' N in 163° 20' W, and 52° 05' N in 176° 50' W.

U.S.S. *Hannibal* - A line of 52 sonic soundings in crossing 30° 12' N in 74° 55' W, 34° 38' 30" N in 74° 51' W, and 37° 07' N in 74° 37' 45" W.

U.S.S. *Houston* - A line of 20 fathometer-soundings taken enroute Yokohama, Japan, to San Francisco, California, crossing 41° 48' N in 154° 56' E and 40° 41' N in 129° 30' W.

U.S.S. *Ramapo* - A line of 924 sonic soundings in North Pacific, enroute Shanghai, China, to San Pedro, California, while crossing 31° 00' N in 128° 47' 30" E, 32° 53' N in 141° 18' E, 33° 01' N in 177° 45' W, and 37° 22' 30" N in 123° 40' W.

U.S.S. *Ramapo* - A line of 1340 sonic soundings in North Pacific enroute Manila, Philippine Islands, to San Diego, California, while crossing 12° 48' N in 124° 17' E, 27° 51' N in 176° 38' E, and 30° 16' N in 137° 19' 30" W.

U.S.S. *Ramapo* - 483 sonic soundings obtained while searching for Los Jardines Island, crossing 21° 38' N in 151° 34' E.

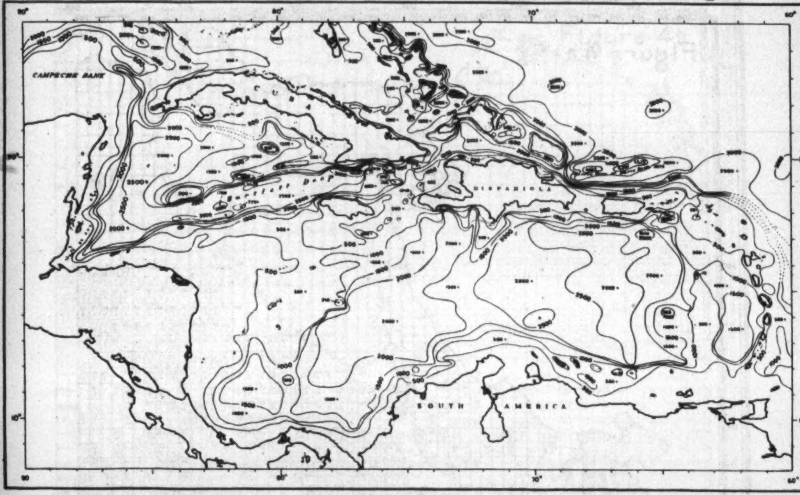
Oceanic depths--The fourth of a series of annual publications presenting lists of oceanic depths in several oceans has recently been published by the Hydrographic Office as Hydrographic Office Publication No. 210C, namely, "List of oceanic depths, 1933, North Pacific Ocean."

This gives the second list of a portion of the sonic soundings in the North Pacific Ocean taken by the U.S.S. *Ramapo* and contains a total of 4696 soundings recorded by the *Ramapo* in 15 crossings of the Pacific Ocean.

The previous lists of soundings published by the Hydrographic Office are as follows: No. 210, 210A, and 210B, containing, respectively, lists of oceanic depths for the North Atlantic Ocean, North Pacific Ocean, and Pacific Ocean.

Unsounded areas of the North Pacific Ocean--Last year I presented to you a chart showing the unsounded areas of the North Pacific Ocean and on which was indicated the portion covered for oceanic areas for which oceanic depths or deep-sea soundings have been observed and recorded on Hydrographic Office charts, as may be noted on the accompanying chart (Fig. 2). Many more soundings will be required to delineate the configuration of that Ocean with any degree of certainty. This year I am presenting to you an amplification of last year's chart consisting of seven more passages by the U.S.S. *Ramapo* across the North Pacific Ocean since January 1932, making a total of 32

BATHYMETRICAL CHART OF THE CARIBBEAN SEA Figure 3



This chart shows the configuration of the Caribbean Sea by depth contour lines at 500 fathom intervals up to and including depths of 4,500 fathoms, according to the records of the U.S. Hydrographic Office, Navy Department, Washington, D.C.

A minus sign on one side of the contour line indicates decreasing depths and a plus sign on the other side indicates increasing depths. Areas of greatest and least depths are indicated by lines leading from them to figures giving their depths in fathoms.

Nares Deep(Puerto Rico Deep) was named in honor of Captain G. S. Nares, R. N., commanding British exploration ship Challenger which on March 26, 1873, obtained a depth of 3875 fathoms in latitude 19°41′N., longitude 65°07′ W.

On January 18, 1902, the U.S.S. Dolphin, Commander A. Gleaves, U.S. Navy, commanding, obtained a sounding of 4662 fathoms in latitude 19°35′N., longitude 67°43′15″W

Bartlett Deep was named in honor of Commander J.R. Bartlett U.S. Navy, commanding the U.S. Coast & Geodetic Survey steamer Blake which obtained a sounding of 3428 fathoms on March 30, 1880, in latitude 19°01′N., longitude 81°02′ W..

The U.S.S. S-21 in October 1928, obtained a sounding of 3770 fathoms in Bartlett Deep in latitude 19°35′ N., longitude 76°31′ W.

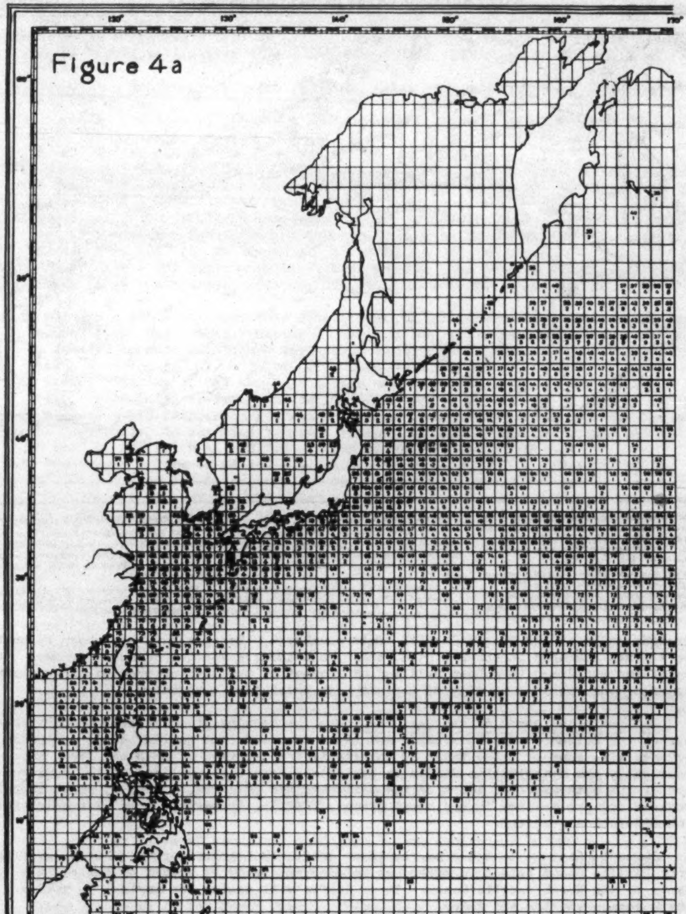
passages on which she recorded 18222 sonic soundings. Her passages are shown by heavy black lines numbered in chronological order, and their direction shown by arrows. But few of her soundings have been utilized on account of the lack of precise information regarding the specific gravity of the water in which they were taken.

Bathymetrical chart of the Caribbean Sea--The results of soundings taken by vessels of the United States Government and those received from various other authentic sources, also some of those taken by the gravimetric surveys of 1928 and 1932, and recorded by the Hydrographic Office on its charts have been utilized in the construction of the bathymetrical chart of the Caribbean Sea (Fig. 3), a copy of which is being prepared for publication in the usual manner, that is, by variation in blue color for each 500-fathom gradient.

Current-charts--The traverse resultant drifts in the one-degree quadrangles of the North Pacific Ocean have been worked up and are now ready to appear on the pilot charts of the North Pacific Ocean. These drifts will assist the mariner in making many a voyage shorter and safer.

Temperature-charts--The publication, on the reverse side of the Pilot Chart of the North Pacific Ocean, of the mean monthly temperatures of the surface-waters of the North Pacific Ocean, summarized from observations of mariners during the years 1904-24, has been completed for the months of December, January, February, March, April, and May. These charts present the number of observations and the average temperature for each one-degree quadrangle for the North Pacific Ocean. Figure 4 shows the chart for the month of May.

Figure 4a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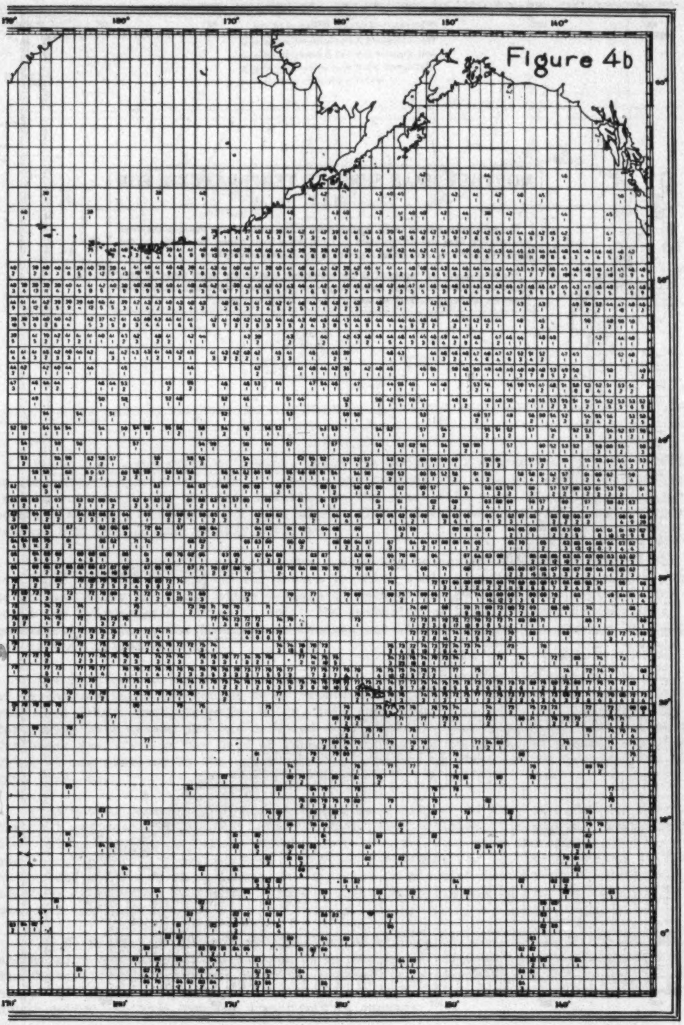

Figure 4b

170°
180°
170°
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30°
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10°
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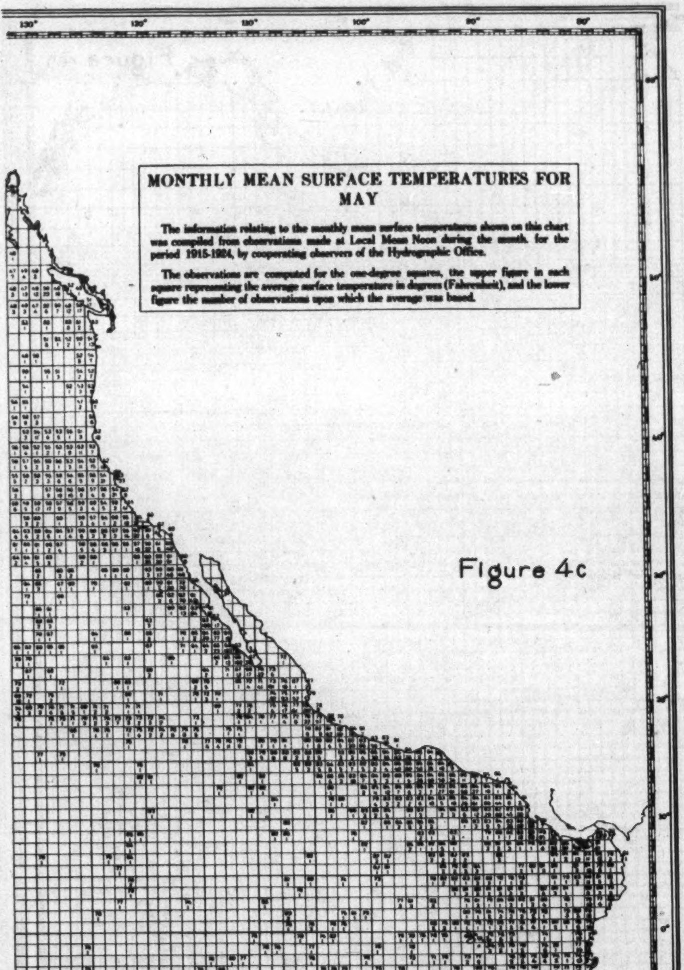


MONTHLY MEAN SURFACE TEMPERATURES FOR MAY

The information relating to the monthly mean surface temperatures shown on this chart was compiled from observations made at Local Mean Noon during the month, for the period 1915-1924, by cooperating observers of the Hydrographic Office.

The observations are computed for the one-degree squares, the upper figure in each square representing the average surface temperature in degrees (Fahrenheit), and the lower figure the number of observations upon which the average was based.

Figure 4c

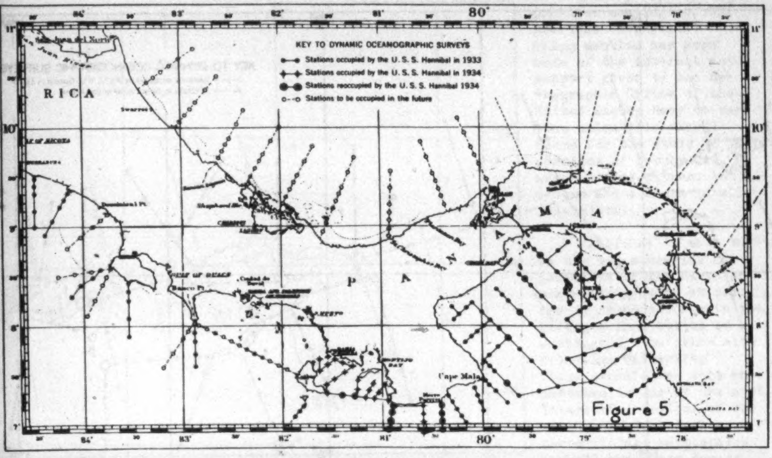

KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS
Stations occupied by the U. S. S. Hannibal in 1933
Stations occupied by the U. S. S. Hannibal in 1934
Stations reoccupied by the U. S. S. Hannibal 1934
Stations to be occupied in the future
84°
83°
82°
81°
80°
79°
78°
11°
10°
9°
8°
7°
RICA
P A N A M A
Cape Mala

Figure 5

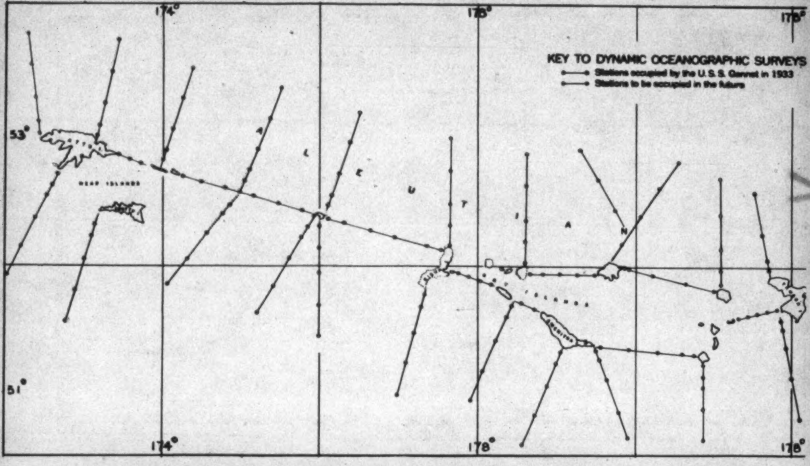
Mechanical extraction of oceanic data--The mechanical extraction of data relating to currents, temperatures, sea and swell, and concomitant data has been continued during the past year, and the data relating to the year 1932, some 200,000 observations covering almost all oceanic portions of the globe, have been completed. Data thus extracted are readily and quickly analyzed.

Dynamic oceanographic surveys--The continuing necessity for obtaining precise values of specific gravity of the waters in which sonic soundings have or may be taken by United States Naval and other vessels to reduce them to their true depths influenced the Hydrographic Office to order the gathering of the necessary hydrodynamic quantitative data by the Hannibal in Panaman and Costa Rican waters, and by the Gannet in Aleutian Island Waters.

The Hannibal during the surveying-season of 1933 occupied 145 stations in all, 44 of which were taken subsequent to my report to the American Geophysical Union last year (see Trans. Amer. Geophys. Union, 14th annual meeting, 1933, pp. 180-193). So far during this season she has occupied 42 stations, reoccupying three stations in the Caribbean Sea, five in the Gulf of Panama, and ten off the coast of Panama, and occupying 24 new stations in the waters south of Panama, as shown on the accompanying diagram (Fig. 5).

The U.S.S. Gannet was fitted with equipment similar to that supplied the U.S.S. Hannibal and described in last year's report. It consisted of a special winch holding 2000 fathoms of sounding-wire, Nansen water-bottles, protected and unprotected deep-sea thermometers, bottom-samplers, titration-appliances for titrating samples of sea-water, and other necessary gear. She operated in Aleutian Island Waters, occupying 42 stations as shown on Figure 6. Figure 7 gives the positions of dynamic stations to be occupied in the future.

R. H. Fleming of the Scripps Institution of Oceanography, La Jolla, California, accompanied the U.S.S. Hannibal, and C. A. Barnes of the Oceanographic Laboratories of the University of Washington, Seattle, Washington, accompanied the U.S.S. Gannet. The assistance rendered by these institutions made possible the success which attended the inauguration of these dynamic oceanographic surveys.


174°
178°
178°
KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS
Stations occupied by the U.S.S. Gannet in 1933
Stations to be occupied in the future
53°
NEAR ISLANDS
A L E U T I A N
51°
174°
178°
178°

Navigators' Sailing Directions or Pilots--The Hydrographic Office issues 56 volumes of navigators' handbooks or Sailing Directions, which supplement the charts with information on oceanic routes, inshore navigation, and ports. Several volumes are revised and reissued each year, and all are brought up to date once each year by means of cumulative supplements. Although written to meet the practical needs of the overseas merchant and Naval vessels of the United States, these books are of unique geographical interest by virtue of their close description of coastal features. The indexes of the various volumes present an aggregate of some 150,000 coastal place names, and the text carries the location and some description of each of these items.

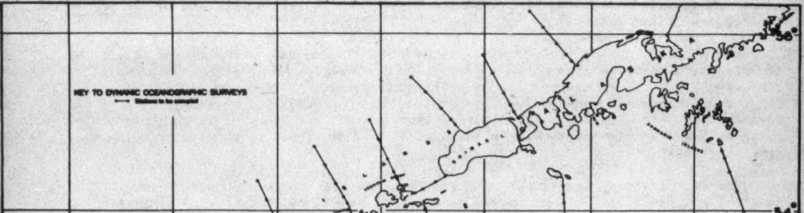

KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS
Stations to be occupied
56°
54°
52°
170°
166°
162°

Figure 7

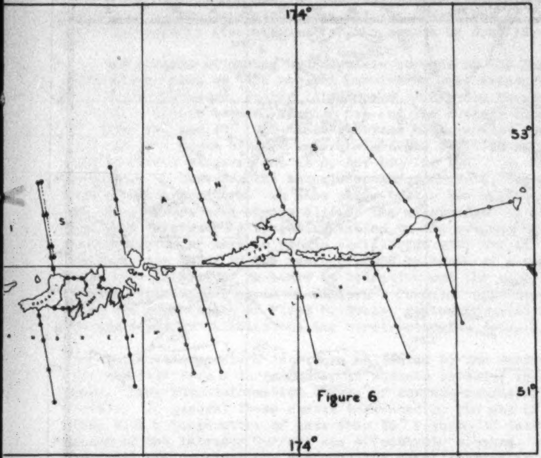


Figure 6

Gravity-reports--At previous meetings of the American Geophysical Union mention has been made of the interest and support given by the Hydrographic Office of the United States Navy to various scientific expeditions for the study of the problems of geophysics which are of extreme interest and concern to all scientists.

Reference is made here to the two submarine expeditions of the Navy for measuring gravity at sea, one in cooperation with the Carnegie Institution of Washington, the other with Princeton University. These expeditions were undertaken in one of the most interesting regions of the world, the West Indies, where violent earthquakes prevail and where danger always lurks in the form of a following destructive tidal-wave, in a locality of great tectonic activity in the Earth's crust, which is now undergoing disturbing changes. In order that some basic study could be made of the real nature of this tectonic phenomenon, gravity-values were needed over the great ocean-deeps and its surrounding waters, for comparison with those obtained at land-stations, and for a complete study of the entire region.

The first report of the expedition of the U.S.S. S-21 in 1928 has been published by the Navy Department and announcement is made today of the final printed report, just off the press, of the second expedition, that of the U.S.S. S-48 of 1932. In this report may be found the final values of gravity for 53 sea-stations as computed by the Hydrographic Office, the positions of which are shown on Figure 8. The report also contains an interpretation of what the gravity-values have revealed in the way of valuable data for scientific study and research. Copies may be obtained from the Hydrographic Office by all those interested in this particular subject.

Magnetic charts--Accurate and late information concerning changing conditions of the Earth's magnetism is of importance to some scientists and particularly to the mariner sailing the world-seas. The Hydrographic Office constructs, and issues to all mariners, world-charts of the values of the magnetic elements of variation, dip, and horizontal intensity laid down as lines of equal values, for all areas either on land or sea, and largely from data supplied by the Carnegie Institution of Washington.

These charts are necessary and essential for the merchant marine whose vessels may not be fitted with the modern gyro-compass, because true courses should be steered between ports, and the value of variation must be known to obtain the compass course. Every navigator requires data for the value of dip and horizontal intensity for utilization in connection with proper compass-compensation.

In cooperation with the Carnegie Institution of Washington, Naval survey-parties have recently made magnetic determinations at Puerto Armuelles, Panama, and at Puntarenas and San José, Costa Rica.

Experience has proven that due to the annual rate of change of the magnetic elements the magnetic charts of the world should undergo reconstruction every five years.

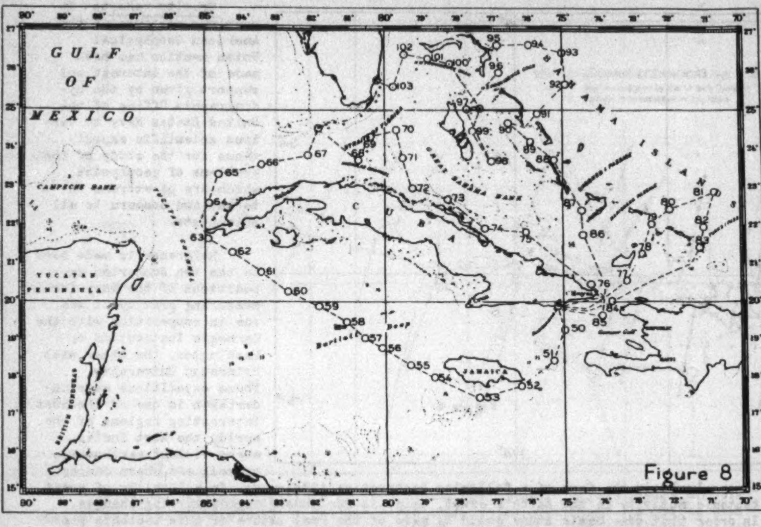

GULF OF MEXICO
CAMPECHE BANK
YUCATAN PENINSULA
BRITISH HONDURAS
C U B A
JAMAICA
GREAT BAHAMA BANK
B A H A M A I S L A N D S
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
90°
85°
80°
75°
70°
27°
25°
20°
15°

Figure 8

I do not wish to bring my remarks to a close without again referring to the destruction of the non-magnetic vessel Carnegie with the hope that some support will be given to the providing of another vessel with similar equipment and scientific personnel to determine the magnetic values upon which the maritime world so largely depends for its safety.

U. S. Hydrographic Office,
Washington, D. C.

THE OCEANOGRAPHIC WORK OF THE INTERNATIONAL ICE PATROL AND ICE OBSERVATION SERVICE CARRIED ON BY THE COAST GUARD IN 1933

R. M. Hoyle

The drift of the ice during the past year differed greatly from the average year in that a great majority of the bergs hugged the eastern coast of southern Newfoundland, thus leaving the eastern slope of the Grand Banks almost entirely free of ice. It is only by the way of the eastern slope of the Banks that the icebergs can drift very far south and form a menace to steamer-lanes between Europe and the United States. Two bergs in February reaching latitude 43° 20' N were the only ones to take this path during the season. During the season it is estimated that 216 different bergs drifted south of latitude 48°, divided into months as follows: January, 0; February, 2; March, 4; April, 12; May, 162; June, 36; July, 0; total, 216. It is seen that most of the ice was concentrated in May and the early part of June.

Due to the peculiarities of the ice-situation during the season, the regular Ice-Patrol cutters were not sent to the ice-regions to maintain a continuous patrol. The oceanographic vessel, General Greene, made six ice-observation cruises in the critical area from March 2 to June 6, 1933. During this time the General Greene carried on the regular duties of the larger patrol-vessels in so far as she was able in regard to locating the limits of the ice and broadcasting ice-information to shipping.

During the middle part of June the cutter Champlain made a final survey of the conditions in the Ice-Patrol area and the operations of the Ice-Patrol vessels in this area were ordered discontinued for the season on June 19, 1933.

The program of making hydrodynamic surveys of the Ice-Patrol regions at frequent intervals as done in 1932 was not carried on last season because of the unusual ice-conditions. However, in the latter part of May the General Greene occupied 25 oceanographic stations between Flemish Cap and the eastern slope of the Grand Banks between latitudes 45° and 48° At these stations observations for temperature and salinity extended to a depth of 1000 meters where the depth of water permitted. Attempts were made to obtain observations at 0, 25, 50, 75, 100, 150, 200, 300, 400, 600, 800, and 1000 meters. However, the actual depths of observations were checked by means of unprotected thermometers. On each water-bottle two reversing-thermometers were used. The thermometers were always allowed ten minutes at the depths of observation before they were reversed. After being hauled to the surface the thermometers were allowed twenty minutes or more to attain equilibrium with the air before they were read. Readings were taken to the nearest 0°005 by means of a magnifying glass. The chlorinities were determined on board by titration and the salinities and densities were determined from tables based on Knudsen's formula. The oceanographic work was performed under the supervision of Floyd M. Soule, Senior Physical Oceanographer. He also made the hydrodynamic calculations and constructed the dynamic current chart of the area.

Surface-temperature data were collected by the General Greene, and reports were also received from a large number of vessels crossing in the vicinity of the Grand Banks. From this information charts of surface-isotherms were drawn for frequent intervals. In general these charts indicated by the end of May 1933 that there was no water with a temperature of less than 36° F south of latitude 45°, and that the eastern branch of the Labrador Current was effectively blocked. This was further borne out by the drift of ice along the Newfoundland Coast instead of down the eastern slope of the Bank. Considering the drift of ice and isotherm-charts, the ratio of the strength of the western branch of the Labrador Current flowing southward along the east coast of the Avalon Peninsula to the strength of the eastern branch of the Labrador Current flowing southward along the eastern edge of the Grand Banks was greater than usual.

After the season was over, the General Greene made a northern oceanographic and ice-observation cruise in Davis Strait, extending as far north as Ivigtut on the Greenland Coast and Hudson Strait on the American side. This cruise lasted from June 26 to July 24, 1933. One hundred and twelve oceanographic stations were occupied during this cruise. At each station temperatures and samples of water for determining the salinity were obtained at various depths from the surface down to the bottom in shoal water and to 2500 meters in deep water. These stations were for the most part reoccupations of the stations taken on the northern cruise of the General Greene in 1931. The data collected are now being analyzed and studied and will be published in the Ice-Patrol Bulletin 19, part 2, dealing with the physical oceanography of Davis Strait.

During this cruise several hundred sonic soundings were taken for which correction-data and accurate positions are available. These are now being worked up and will be published soon.

On the northern oceanographic cruise the first ice was sighted near the coast 60 miles south of the Strait of Belle Isle. Bergs were numerous close inshore from there to the Strait of Belle Isle. In the Strait bergs were numerous with scattered bergs extending about 50 miles offshore. Off the Greenland Coast we passed two bergs 80 miles to the southeast of Cape Farewell and met heavy pack-ice 25 miles off the coast. Little else could be learned of ice-conditions between Cape Farewell and Ivigtut, because of dense fog. Around Ivigtut there was no pack-ice. Bergs were numerous, extending about 40 miles offshore. Between 40 miles and 110 miles offshore we sighted four bergs a few miles north of the latitude of Ivigtut.

Proceeding westward we met pack-ice, with open lanes 20 miles offshore from Resolution Island. Forty miles offshore it was closely packed. The same conditions prevailed off Nachvak Bay. At Port Manvers the pack-ice extended only 20 miles offshore, and disappeared entirely a few miles south. Many bergs were sighted in the pack-ice. Two bergs were 130 miles offshore east of Nachvak Bay. Off Port Manvers the eastern-most bergs sighted were 55 miles offshore. Bergs were very numerous close inshore along the Labrador Coast southward to Belle Isle.

During the current year no changes are contemplated in the method of conducting the Ice-Patrol. Two cutters will maintain a continuous patrol in the ice-regions during the ice-season (usually April, May, and June). The General Greene will make frequent oceanographic surveys in the vicinity of the Grand Banks and much the same program as in previous years will be carried on. The surface-isotherm charts will also be constructed as in former years. After the discontinuance of the Ice-Patrol, the General Greene will make a cruise of about three weeks' duration in Davis Strait. She will occupy approximately 65 oceanographic stations, making a modification of the cruise she made in 1933. Ice-conditions in this region will also be noted. Echo-soundings with the fathometer will be made at frequent intervals.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

R. R. Lukens

The oceanographic work of the Coast and Geodetic Survey for the past year has been confined largely to the offshore surveys on the Atlantic, Gulf, and Pacific coasts. These surveys have been extended to the limit of the continental shelf or to depths of one to two thousand fathoms. This work is all being controlled by radio-acoustic sound-ranging and is resulting in an accurate delineation of the floor of the ocean over which the surveys extend.

Previous surveys consisted for the most part of a few offshore lines controlled by dead-reckoning and astronomical sights. We find that many of the great submarine valleys and gorges which exist along the edge of the continental shelf were either missed entirely or imperfectly developed by the earlier surveys. In some cases we have found that the 100-fathom curve was formerly charted as much as 5 miles in error.

The development of echo-sounding and its adoption by most of the large vessels of the merchant marine and Navy have made it important that the 100- and 1000-fathom curves be developed with an accuracy hitherto considered unnecessary. It is only with the introduction of radio-acoustic sound-ranging that such surveys are now possible.

The survey-ship Oceanographer together with the Lydonia and the Gilbert has been engaged on offshore surveys off the coasts of Maryland and Virginia. They completed a full season in 1933, and started the season of 1934 about April 15. They start at the beach and carry the hydrography offshore to the 1000-fathom curve. An important feature of the work is dragging for and locating wrecks along the steamer-tracks, and searching for shoals which have been reported from time to time by merchant and naval ships. From the work of last summer there is evidence that many of the shoals along the coast are not stable, but are continually shifting.

Control is carried offshore by means of buoy triangulation, the distance between buoys being determined by radio-acoustic methods and the direction between buoys by Sun-azimuths. The Oceanographer is equipped with the British taut-wire measuring apparatus which has been found very useful for the accurate measurement of distances at sea. By actually measuring the distances between selected pairs of buoys, the triangulation is strengthened and frequent velocity-tests throughout the season may be made.

During the season of 1933 excellent results were had with the radio-acoustic method at the start of the work, but early in the summer a severe storm seemed to change the acoustic properties of the water. After this storm, bombs could be carried only a fraction of the distance that had been obtained at the start of the work. It was several weeks before the transmission of sound through the water became normal again. Just why this storm should affect sound-ranging is not entirely clear, but all evidence indicates that the change came with the gale.

In connection with this work, serial temperatures were taken at many stations over the area and many density-observations were made. The station vessels while anchored at the various buoys made constant current-measurements and temperature-observations twice daily.

On the Gulf Coast the ship Hydrographer was engaged the entire year on inshore and offshore surveys. Hydrography controlled by radio-acoustic sound-ranging was extended to and beyond the 100-fathom curve, which is about 120 miles offshore. A large number of serial temperatures and density-observations were taken over the area. Here, as on the Atlantic Coast, shore hydrophones can not be used, and it is necessary to use floating hydrophone stations.

It was found that close inshore where the water is shoal, the range of the bombs was short, usually seven to ten miles, while as the survey proceeded offshore the range gradually increased to 30 to 40 miles, or all that was required. The Commanding Officer of the Hydrographer believes that the suspended matter in the inshore waters is an important factor in limiting the range of bombs in that area. He noted that when a wind arose and stirred up the water to the extent that it became cloudy, the range of the bombs decreased.

On the Pacific Coast the ships Guide and Pioneer continued offshore surveys along the California coast between Monterey Bay and the Santa Barbara Channel. On this coast the floating hydrophone stations are not necessary and shore stations are used. The radio-acoustic method has reached its greatest success on the Pacific Coast. At certain times the two ships used each other's stations and frequently returns were had from four shore-stations, some of which were more than 100 miles distant. By using all available data in computing the velocities, the four arcs usually made a remarkably small triangle of error.

These vessels collected 140 surface-samples and 77 bottom-samples of water which were forwarded to the Scripps Institution of Oceanography at La Jolla, California, for chemical titration. In addition, they made 234 observations of surface-temperatures.

Towards the end of last season the two vessels cooperated in a series of experiments to ascertain more knowledge of the path of the sound-wave through the water. Bombs were exploded in depths up to 600 fathoms and hydrophones were suspended in depths up to 850 fathoms. A large number of oscillograms were taken and it is hoped that sufficient data were obtained to shed some additional knowledge on this very interesting subject. The field-party has not yet finished its preliminary analysis and the final results cannot yet be announced.

The two vessels discovered several hitherto unknown submarine mountains and ridges and have developed several unsuspected submarine valleys which when charted will be of much value to fathometer-equipped ships in following the 100-fathom curve along this foggy and dangerous coast.

The ships Surveyor and Discoverer continued surveys in Alaska in the vicinity of Kodiak and Middleton Islands. They obtained 1003 temperature-observations and 492 density-observations. Both of these ships run deep-sea sounding-lines across the Gulf of Alaska in going to and from their summer working grounds, and that area is being gradually filled with soundings. The lines are laid out ten miles apart.

During the season of 1934 these vessels will be engaged in offshore work in Bering Sea and the Pacific in the vicinity of Unimak Pass in western Alaska. This will cover a new field where very few soundings or temperature-observations have ever been made.

Until June 30, 1933, when she was laid up because of lack of funds, the Pathfinder was at work on the western coast of the Island of Palawan, Philippine Islands. An important feature of her work was the delineation of the western edge of Palawan Bank, a coral bank extending about 30 miles off the west coast of the Island, and abounding in shoals which menace shipping between these islands and European ports. This Bank has also been the subject of much discussion among oceanographers, and particularly among students of the coral problem. At the time the survey was discontinued, this ship had discovered three submerged atolls, each about five miles in diameter and closely adjacent. They lie on the western extremity of the Bank, and the rims rise abruptly to within three fathoms of the surface from a depth of 40 fathoms on the Bank, and approximately 200 fathoms on the China Sea side. There are depths of 25 to 40 fathoms within the atolls, and the bottom is soft mud. The details of the survey of these atolls, in addition to the commercial importance, should offer most valuable material to scientists at work on the coral problem. The fathometer has again proved its importance here in making possible a detailed survey of such a difficult area with safety to the vessel and personnel engaged on this work.

The tidal work of the Survey has gone forward with accelerated activity. Primary stations for securing basic tidal data number 32, and are distributed as follows: Eighteen on the Atlantic Coast; four on the Gulf Coast; seven on the Pacific Coast; two on the Alaskan Coast, and one in Hawaii. Observations have been secured during the year at 20 secondary stations.

An increasing number of hydrographic surveys during the year has greatly added to the number of new short series of tide stations, and records have been received from 122 such stations.

A tide survey of the Oregon Coast has been in progress during eight months of 1933 and will be continued until a year of record has been secured at twelve selected stations along the coast. In addition, seven stations have been established at subordinate points where a series of a month or more have been observed. Bench-marks at each station have been connected to each other by first-order levels and, in turn, to the general first-order level net of the country. A large amount of data relative to tidal ranges and planes is being obtained, and it is expected that the results secured will furnish for the first time in this locality material for determining sea-level elevations, and the slope, if any, of sea-level along the open coast of Oregon.

A tidal survey of the west coast of Florida, which was started in 1933, will be completed this year when a series of twelve months of continuous records at seven stations will have been obtained. The tides in this area are very complicated, as is true all along the Gulf Coast, being diurnal or semi-diurnal according to locality and time of month, and data for this particular area is very much needed.

It is proposed to conduct a tidal survey of the Washington Coast during the coming year similar to the Oregon and Florida surveys. Observations for twelve months at two outside stations and ten along the shores of the Straits of Juan de Fuca and Puget Sound, as well as several subordinate stations, will be obtained.

Unusual high-waters were observed in the Chesapeake Bay area due to abnormal weather-conditions August 23-24, 1933. At Washington the high water rose eight feet above mean high-water; at Bladenburg, 10.6 feet; at Baltimore, 7.2 feet; and Hampton Roads, 6.4 feet. Delaware Bay, being somewhat outside the path of the hurricane, was not disturbed as much as Chesapeake Bay and the tide at Philadelphia rose only 2.7 feet above mean high-water.

A comprehensive current and tide survey was completed in the St. Johns River, Florida. Observations were secured at 35 current and 15 tide stations. A 15-day current series was obtained at the mouth of the River, the data thus obtained being used to furnish daily predictions for including in the current tables. Scattered along the coast there were obtained, in addition to the St. Johns River, observations for 122 current stations. During the coming year it is planned to obtain a 29-day series at the entrances to Galveston and to San Diego, and arrangements are also being made for a comprehensive tide and current survey along the Savannah River.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SURFACE-TEMPERATURES ON THE NEW YORK TO CAPE SÃO ROQUE STEAMSHIP-ROUTE

Phil E. Church[1]

Early in 1932 the Brazilian Traction and Light Company installed thermographs on three of their vessels which ply between New York and Cape São Roque and thence to

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[1] Contribution No. 49 from the Woods Hole Oceanographic Institution.

South American ports. Twenty-one southbound trips furnished the data for the preliminary survey of the line over which these vessels traveled. The period of investigation was from January 1932 through August 1933. The vessels plied over a great-circle route which, passing north of Bermuda, transversely cut across the continental shelf, the slope-area, and the Gulf Stream, and passed obliquely across the Central Atlantic area and the North Equatorial Current.

The accuracy of the instruments was of a high order and only infrequent adjustments were necessary, which were made by officials when the vessels were in either New York or Santos.

Only the Central Atlantic and North Equatorial Current areas will be discussed here because the surface-temperatures of the continental shelf, the slope-area, and the Gulf Stream have been treated in papers by Bigelow (H. B. Bigelow, Studies of the waters on the continental shelf, Cape Cod to Chesapeake Bay, Part I, The cycle of temperature, Papers in Physical Oceanography and Meteorology, published by Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, 1933), Harwood and Brooks (E. M. Harwood and C. F. Brooks, Monthly sequence of sea-surface temperatures on the New York-San Juan steamship-route, Trans. Amer. Geophys. Union, 14th annual meeting, 1933, pp. 173-180), and Church (P. E. Church, Surface-temperatures of the Gulf Stream and its bordering waters, Geog. Rev., v. 22, No. 2, pp. 286-293; also Progress in the investigation of surface-temperatures of the western North Atlantic, Trans. Amer. Geophys. Union, 13th annual meeting, 1932, pp. 244-249).

Central Atlantic Water--South and east of the Gulf Stream lies that great, wide expanse of uniformly warm water. To the north and west its limit is sharply marked by the Gulf Stream, but its southern edge is most indefinite. Criteria other than surface-temperature will probably have to be employed in finally defining the exact limit, if an exact limit is to be made. Harwood and Brooks, on the New York to San Juan steamship-route, placed the southern edge at that point where there was no further increase in temperature with a decrease of latitude. They found that the Central Atlantic Water, on its western edge, was broader in winter than in summer. The lesser width in summer is ascribable, for the most part, to the more northerly position of the summer Sun. As the Central Atlantic loses in width, the Antilles Water to the south gains in width, and the loss in width of one is compensated for by a corresponding gain in width of the other. Only to a certain extent does this apply to the waters farther east where the Brazilian Traction and Light Company vessels cross. It is true that here the Central Atlantic Water is narrower in summer and wider in winter, but the corresponding loss or gain is not entirely made up from the next band of water to the south but from the next two bands. Also, the width of the Central Atlantic Water has a far greater seasonal fluctuation here than to the westward. If we may strike an average for the yearly position of the southern limit, using the criterion of Harwood and Brooks, it would be found at approximately latitude 24° north and longitude 53° west (longitude of Cape Race, Newfoundland). From this average position there is a shift of at least three degrees of latitude north or south, depending upon the season. The northern boundary lies somewhere near latitude 27° north in late summer (early September) and six months later this same boundary is found in the neighborhood of latitude 21° north. This shift of boundary of 300 to 400 miles in latitude cannot be laid to any great floodings of warmer surface-water; for the present it must be assumed to be the result of the shift of the Sun.

Winter temperatures--Minimum temperatures occur in late February or early March for this area as a whole. At this time the lowest temperatures are to be found just south of the Gulf Stream. Here the water is between 19° and 20° C. Southward there is a gradual increase in surface-warmth to approximately the parallel of 26° where a sudden rise of one degree or more brings the temperature to 23°.5 or 24° C. From this position to the parallel of 21° there is an increase in temperature of only one degree and south of that the surface-warmth remains quite constant for at least another 300 miles more. The rise of temperature amounts to but five or six degrees within 16 degrees of latitude. We may consider the southern edge of this body at this season to be latitude 21° north.

Summer temperatures--Maximum temperatures are reached by the latter part of August or early September. Again the coolest water is just south of the Gulf Stream, north of Bermuda. Here the thermographs register 27° C, and fractionally higher towards Cape Hatteras. To the south, at latitude 30° north the temperature is slightly above 28° C, and increases slowly to the highest temperatures along this route somewhere in the vicinity of latitude 27° north where the superficial layers may be from 29°.5 C to 30° C. The exact position of this high degree of heat varies somewhat from year to year, but a rise of two or three degrees is experienced in this body at this season in the latitudinal range of six to ten degrees.

Annual range--Nowhere over the western part of this body of water does the annual range exceed ten degrees. The annual range is greatest on the extreme western part (over the New York to San Juan route) where it is nearest the continent. North and east of Bermuda, on the New York to Cape São Roque route, the annual range is between eight and nine degrees, while south of the parallel of 30° it diminishes gradually and evenly to six degrees at latitude 24° north. It appears that this line of six degrees of annual range may tentatively be used as the southern boundary of the Central Atlantic Water. It coincides quite closely with the position of that boundary as formulated by Harwood and Brooks and also agrees largely with Schott's southern boundary of the Sargasso Sea where the weed Sargassum is "sehr hauf" (G. Schott, Geographie des Atlantischen Ozeans, Tafel 26, p. 264, 1912). However, this limit is considerably south of the limit of normal salinity (36.5) of the Central Atlantic Water which Iselin (C. O'D. Iselin, unpublished manuscript, 1933) states to be in the neighborhood of latitude 28° 30' north.

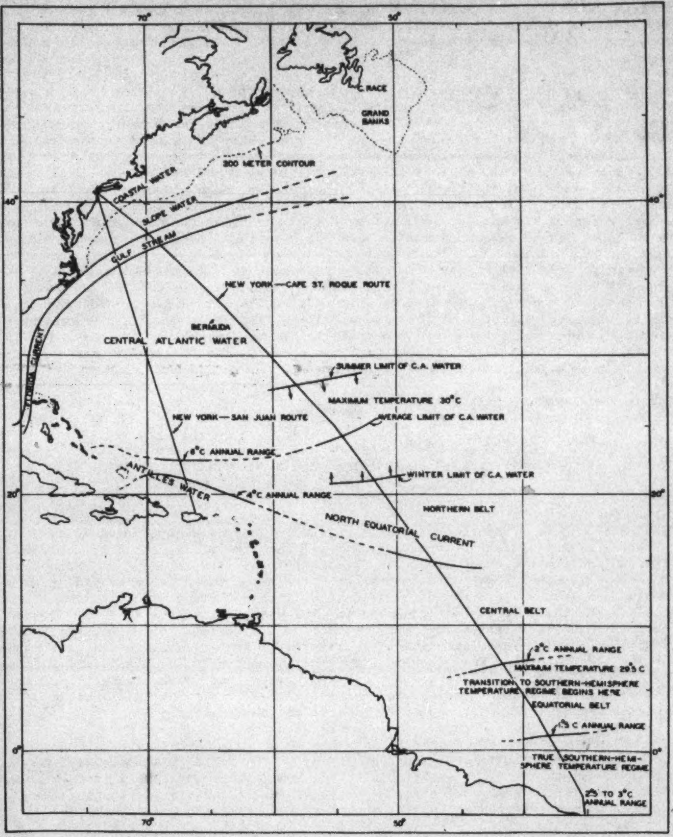
North Equatorial Current--South of the Central Atlantic Water on the New York to Cape São Roque route is the broad expanse known as the North Equatorial Current. It is at least 1500 miles wide, latitudinally, and is composed of a complex of at least three different types of water which can be distinguished on the basis of surface-temperature characteristics. These different bodies agree, in a large measure, with bands of different salinities. This leads to the assumption that the water of each comes from a somewhat different source, or has differing factors influencing the physical properties. From north to south the following belts are found: From the southern edge of the Central Atlantic Water to the vicinity of latitude 15° north; from latitude 15° north to approximately latitude 7° north where the annual regime of temperatures of the northern hemisphere undergoes a shift from the normal; south of latitude 7° north to Cape São Roque. These subdivisions will be identified as the "northern belt," the "central belt," and the "equatorial belt."

Northern belt--The outstanding surface-temperature characteristic of this subdivision is the almost total lack of latitudinal gradient at any one season. From north to south there is a rise of not more than one or one and a half degrees. This occurs in the winter for in summer the reverse is apt to be true, that is, the warmer water being on the northern edge of the belt. This northern edge has an annual range of about 6° during the year and about 4° on its southern edge (latitude 15° north). In late summer the maximum temperatures may reach 30° C next to the Central Atlantic Water and fractionally lower farther south. In late winter the northern edge cools to minimum of 25°.5 C and 26° C along its southern edge.

This northern belt corresponds to what Iselin (unpublished manuscript, 1933) has called a horse latitude, high salinity-belt. The high salinity (37) is thought to result from the great evaporation caused by high temperatures, little wind, and low humidity from the descending air of the North Atlantic (Azores-Bermuda) high-pressure belt.

Central belt--Latitudinally this belt is about 500 miles wide. Its northern edge is poorly defined as regards temperature, the only indication of a boundary occurring in the months of February, March, and April when there is a slight break in temperature of a half to a whole degree. A small change, such as this, would mean little or nothing in the water of the extra-tropics, but within the tropics where there is a small annual range, a distinct break in temperature is, perhaps, sufficient justification for use as a boundary. Furthermore, the water here corresponds to the trade-wind belt where the water is less salty (36.25) than that to the north. The southern edge of this belt is marked not only by a change in the annual march of temperature, but also a change in the salinity for the water is considerably fresher.

The annual range of temperature in this belt is even less than the northern belt for the range amounts to only 3° or 4° at most. This is owing, no doubt, to the lower


70°
50°
40°
20°
0°
C. RACE
GRAND BANKS
200 METER CONTOUR
COASTAL WATER
SLOPE WATER
GULF STREAM
FLORIDA CURRENT
NEW YORK—CAPE ST. ROQUE ROUTE
BERMUDA
CENTRAL ATLANTIC WATER
SUMMER LIMIT OF C.A. WATER
MAXIMUM TEMPERATURE 30°C
NEW YORK—SAN JUAN ROUTE
AVERAGE LIMIT OF C.A. WATER
6°C ANNUAL RANGE
ANTILLES WATER
WINTER LIMIT OF C.A. WATER
4°C ANNUAL RANGE
NORTHERN BELT
NORTH EQUATORIAL CURRENT
CENTRAL BELT
2°C ANNUAL RANGE
MAXIMUM TEMPERATURE 29.5 C
TRANSITION TO SOUTHERN-HEMISPHERE TEMPERATURE REGIME BEGINS HERE
EQUATORIAL BELT
1.5 C ANNUAL RANGE
TRUE SOUTHERN-HEMISPHERE TEMPERATURE REGIME
2.5 TO 3°C ANNUAL RANGE

latitude of the central belt and also to the condition of water a degree or more warmer than the southern edge of the northern belt at the time the latter belt has reached its minimum temperature. The distinctly higher temperature of the central belt in late winter and the smaller annual range seem to indicate that the water of the central belt remains within the tropics for a longer period than that of the northern belt. The minimum occurs in February when the surface is between 25.°5 C and 26° C and the maximum comes in September when the temperature is 28.°5 C to 29° C. At the period of maximum temperature both the Central Atlantic Water and the northern belt may have a surface-temperature slightly higher than the central belt.

Equatorial belt--In the vicinity of the parallel 7° north of the equator northwest of Cape São Roque, there is a decided shift in the annual regime of surface-temperatures. Except from July through November, there is a sharp increase in surface-warmth contrasted with the central belt. From July through November the temperature remains about the same as that to the north, but along the adjacent boundaries of the two subdivisions there are streaks of warmer and cooler water as suggested by the thermograph pen.

Annual march of temperature--As far south as latitude 2° north the minimum temperatures occur in early February and are followed by a slow warming until May or early June when a secondary maximum occurs. June, July, and August are somewhat cooler than the late spring maximum, but toward the end of summer warming is again evident. During October and November the temperature rises to another peak, this being the primary maximum. Near the northern edge of this belt the temperature may reach 29°.5 C at this time. After the maximum has been attained, the drop in temperature is rapid until the minimum in February. The northern part of this belt has an annual range of from 2° to 2°.5. Just north of the equator (about latitude 2° north) in the middle of this equatorial belt the annual range amounts to only 1°.5 with a maximum of 28°.5 in November.

Between the parallel 2° north of the equator and Cape São Roque the shift to the southern hemisphere temperature-regime is nearly completed. The maximum temperatures come in February, March, and April from which period the warmth slowly declines to a minimum during July, August, and September. Only a vestige of the November maximum exists. The annual range is slightly more here than in the belt to the north for it amounts to 2°.5 to 3°. However, a lower minimum accounts for the greater annual range because the July-August temperatures get as low as 26° C or 26°.5 C.

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TEMPERATURE-SALINITY CORRELATION WITHIN THE FLORIDA CURRENT

C. O'D. Iselin[1]

The observations of the *Bache* Expedition (1914) enabled Wüst (Florida- und Antillenstrom, Veroff. Inst. Meereskunde, N.F., Reihe A, Heft 12, pp. 1-48, Berlin, 1924) to publish a curve which gives the relationship between temperature and salinity for the waters flowing through the Straits of Florida. A careful comparison of this curve with observations from the Sargasso Sea shows that for any given temperature between 15° and 6° the Florida Current Water as it leaves the Straits is from 0.05 to 0.20 parts per thousand less saline than water from the Western North Atlantic in similar latitudes. These lower salinities are especially striking in the deeper parts of the Current. For example, Wüst's curve shows that 6°-water in the Straits of Florida has a salinity of about 34.84 parts per thousand, while from recent *Atlantis* observations we know that the same temperature in the Antilles Current or in the Sargasso Sea would give a salinity value of about 35.03 parts per thousand.

The explanation of this situation is not hard to find. From the *Dana* Expedition (J. P. Jacobsen, Contributions to the hydrography of the North Atlantic, The *Dana* Expedition 1921-22, pp. 1-98, Copenhagen, 1929) we know that the relatively fresh intermediate (700 to 1200) layer, which is the dominant feature of the whole South Atlantic, can be easily traced north of the equator for some distance. Wüst (Der Ursprung der Atlantischen Tiefenwasser, Jubilaums Sonderband, Zs. Ges. Erdkunde, pp. 506-534, 1928) found that in mid-ocean this fresh layer of antarctic origin extends to about latitude 20° north. Recent observations in the Caribbean Sea show that this southern water penetrates between the islands of the Lesser Antilles and spreads north and west towards the Yucatan Channel. It is understandable then that the colder waters of the outflow from the Straits of Florida should have relatively low salinities reflecting their origin from the Equatorial Current. Thus the current-system of the Caribbean and the Gulf of Mexico carries some of the antarctic layer considerably further north than it is able to spread in mid-ocean.

Since the deeper waters in the Straits of Florida can be distinguished by their relative freshness, it would be interesting to learn how far northward this remnant of antarctic water can be traced in the Florida Current. Three important sections, made by the *Atlantis* during May 1933, have provided us with ideal material for this study. The first of these crossed the current off Cape Canaveral, 75 miles north of the mouth of the Straits. The next ran eastward from Jacksonville, Florida, while the third was located off Onslow Bay, about 115 miles south of Cape Hatteras. Thus we can examine the average ratio of T to S at mid-depth in the heart of the Current at three points between the Bahama Banks and Cape Hatteras. The results are tabulated in Table 1.

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[1] Contribution No. 51 from the Woods Hole Oceanographic Institution.

Table 1--Salinity, S, in parts per thousand at different temperatures, T

Region	Temperature					
	6°	7°	8°	9°	10°	11°
Florida Straits (Wüst)	34.84	34.88	34.93	35.01	35.15	35.30
Cape Canaveral	.....	34.88	34.96	34.08	34.22	35.36
Jacksonville	.....	.....	35.02	35.12	35.23	35.38
Onslow Bay	35.04	35.06	35.12	35.14	35.22	35.36
Sargasso Sea (average)	35.03	35.07	35.12	35.20	35.29	35.41

Since off Cape Canaveral and Jacksonville the Current is flowing over the relatively shallow Pourtales Plateau, its depth is there limited to about 800 meters and water as cold as 6° does not appear in the sections. Thus we learn that the bottom-water from the deeper parts of the Straits of Florida is not able to flow northward and that after the Current has left the Pourtales Plateau (off Onslow Bay), typical Sargasso-Sea Water is found in the layers colder than 8°. But the water warmer than 8° still bears the stamp of its southern origin as it approaches Cape Hatteras.

We can conclude then that as the Florida Current flows northward along the continental slope, it is constantly increasing in salinity at mid-depths through the admixture of the more saline waters of the Sargasso Sea. But as the Current approaches Cape Hatteras, there still remains in the layer having temperatures of from 9° to 11° some traces of its South Atlantic origin.

Further studies of this question are now in progress and a full examination of the available observations from the heart of the Gulf Stream north of Cape Hatteras is now being made with a view of finding just how far the low salinities at mid-depths in the Caribbean can be traced. It is rather startling to discover that the Gulf Stream, so long considered as carrying tropical waters northward, really has at mid-depths a considerable admixture of water of antarctic origin.

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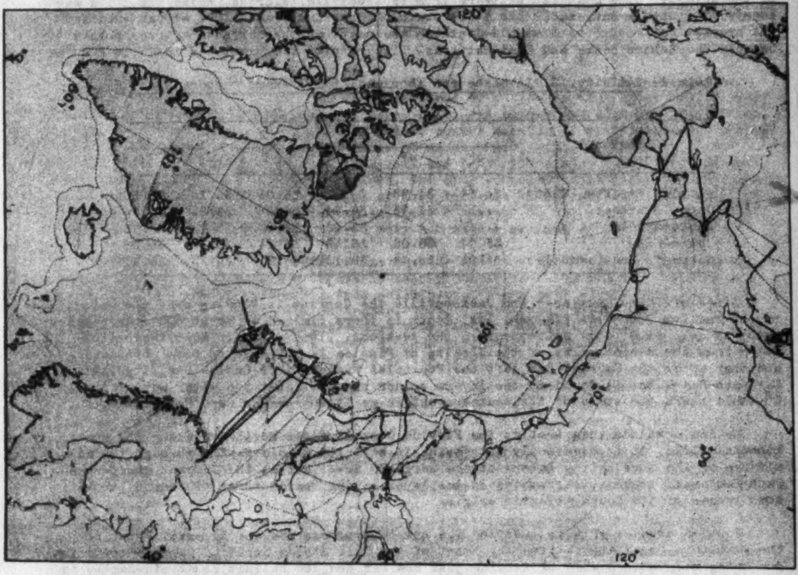
RECENT OCEANOGRAPHIC WORK IN THE RUSSIAN ARCTIC

H. A. Bauer

In appraising the oceanographic work carried out by a number of Russian institutions during recent years, clear distinction must be made between those expeditions which were sent out for purely oceanographic work and those whose oceanographic program was coordinated with and often subordinated to the aims of an economic or trade expedition.

While this latter category of research was necessarily limited in scope and sporadic in achievement, the purely oceanographic expeditions have pursued a well-planned survey over definite sections of the polar shelf, especially within the more accessible western part of the Russian polar seas.

Outstanding among these expeditions are the following: The voyage of the ice-breaker Sedov into the northern part of the Barents Sea including the sounds of Franz Josef Land, 1929; the voyage of the same boat into the northern part of the Kara Sea, 1930; the three consecutive voyages of the H. Knipovich, 1930, 1931, and 1932 along the Kola Meridian and into the region between Spitsbergen, Franz Josef Land, and Novaya Zemlya; the Spitsbergen Voyage of the Persey, 1933; and finally the Bering-Sea Party of the trawler Dalnevostochnik, 1932.



Of those expeditions whose mixed objectives permitted only of occasional oceanographic work, the following may be mentioned: The voyage of the Sibiriakov through the Northeast Passage, 1932; the voyage of the same boat to Cape Chelyuskin, 1933; the Taimyr Hydrographical Survey-Expedition, 1932; the Kolyma River Trading-Expedition, 1932, 1933; the voyage of the Krassin (transport-expedition) to the mouth of the Lena River, 1933; the voyage of the Icebreaker Soviet to Wrangel Island, 1932; and the winter voyage of the Krassin into the Pechora Sea.

The first-mentioned group of expeditions has laid down a well-organized series of over 300 deep-sea stations, all of which have received exhaustive oceanographic evaluation. Evidently, much effort has been spent in obtaining a maximum of straight profiles, the majority trending either north-south or east-west. In appraising the value of profiles taken in ice-infested waters, careful consideration must be given, however, to the often considerable time-interval between neighboring stations. Most of the stations are, of course, on the continental shelf and extend, therefore, rarely beyond 450 meters; only a small number of profiles, on the extreme east and west, extend into depths between 2000 and 3000 meters. All stations, except those in the Pechora Sea, were taken during the summer months.

The main objective of the profile-work was a thorough examination of the movement of the shelf-waters and of a possible exchange of shelf-water with the warmer water from the Polar Basin. In many instances, especially in the northern section of the Kara Sea, a well-marked penetration of water from the Atlantic middle layer of the Polar Basin could be observed. Likewise conspicuous was the frequent observation of a minohaline surface-layer in the Kara Sea, due to the discharge of Yenisei and Ob, an influence which could be traced almost to the edge of the continental shelf.

Both the Barents Sea and the Kara Sea have been covered by a network of surface-observations sufficiently close for charting the surface-movements of the water from surface isohalines and isotherms rather than using the dynamic topographical method. It seems that the lack of a close network of deep-sea stations taken within a reasonably short period of time has so far prevented the Russian investigators from evaluating their data by the Bjerknes method. Only one expedition had occasion to run four parallel profiles from two boats in a limited area (betwen Dickson Island and Sverdrup Island) so that the surface-currents could be portrayed dynamically. As a rule, any boat engaged in either major or minor oceanographic work kept a complete record of surface-observations (temperature and salinity) practically for every hour of each trip, thus contributing to a huge store of information on surface-conditions.

In addition to this routine work a great deal of special research was achieved. Much attention was necessarily devoted to the ice. Beside recording and charting ice-conditions in monthly synoptic charts, considerable new information has been gained as to the influence of melting ice upon the distribution of the chemical elements of sea-water, and about the ice itself. Systematic chemical examination of ice-samples have, for instance, led to the discovery that the relation of sulfate to chloride and especially that of alkalinity to chloride may be used as an excellent criterion for the age of the ice.

Other investigations added to the existing knowledge on the density of sea-ice, its rate of evaporation, and on the causes of colored ice, especially brown ice which has been found to decrease the salinity of the surrounding water to a surprising degree. Transparency and color of sea-water have likewise been objects of special research. One of the veterans of the Russian arctic, the Krassin, carried out a considerable series of parallel determinations of salinity by chemical, optical, electrometrical, and hydrometrical methods.

The release of many hundreds of drift-bottles and of a great number of drift-buoys, the occasional taking of plankton and of benthos stations, the instrumental determination of diurnal sets of tidal currents, and finally a considerable record of echo-soundings complete the elaborate program of work done in recent years within the Russian Sector of the arctic.

Considering the tremendous handicaps of ice and of a short navigating-season, the quantity as well as the variety and quality of the work is surprising. Never before in the history of polar research has such a great number of sturdy boats and of intrepid men penetrated into the domain of ice and icy waters, wresting from them such a store of valuable information.

In the preparation of this paper and the accompanying chart the following references were consulted: Transactions of the Institute for the Exploration of the North, Moscow, 1931; bulletins of the Arctic Institute, No. 1-11, Leningrad, 1933; Transactions of the Arctic Institute, volumes 1 and 10, Leningrad, 1933; and Arctica 1933, volume 1, Leningrad, 1933.

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A PRELIMINARY COMPARISON OF MONTHLY WEATHER WITH OCEAN-TEMPERATURE SEQUENCES IN THE WESTERN ATLANTIC REGION

Charles F. Brooks and E. Monroe Harwood

The main reason for the installations of numerous sea-water thermographs on commercial steamships in the western Atlantic since 1926 has been to provide accurate sea-temperature data for comparison with weather ashore, in order to find out to what extent the slowly changing sea-temperatures can be used to anticipate seasonal weather abnormalities (see Charles F. Brooks, Gulf Stream studies--General meteorological project, Mon. Weath. Rev., v. 58, pp. 103-106). A first sampling was mentioned in a paper by the authors in 1933, when it was shown that air-temperatures at Blue Hill varied more or less in unison with the sea-temperatures, but with a suggestion of a delayed effect (Monthly sequence of sea-surface temperature on the New York-San Juan steamship-route, Trans. Amer. Geophys. Union, 14th annual meeting, 1933, pp. 173-180). The present paper provides another sampling, in the form of a closer comparison between temperature and precipitation at Boston and Baltimore, on the one hand, and the preceding sea-temperatures by zones of two degrees of latitude on the route between New York and Bermuda, on the other hand. The thermograph-records were obtained on Negretti and Zambra instruments bought by the Furness-Bermuda Line and installed under the supervision of Benjamin Parry of the United States Weather Bureau in New York. Mr. Parry checked the instruments from time to time, and the records were filed at the central office of the Weather Bureau in Washington. The thermograms were reduced chiefly by E. Monroe Harwood at the Woods Hole Oceanographic Institution, and the data were summarized by him and Richard F. Baker at the Blue Hill Observatory. Mr. Baker also obtained the means and departures of the Boston and Baltimore weather-data used. The study was financed chiefly by a gift from Arthur Rotch of Boston.

The monthly sea-temperatures by degrees of latitude were averaged by months from November 1928 to March 1933, and the departure of each month's temperature was determined. These departures for single degrees of latitude were then combined by pairs, to provide a broader basis for comparison, as follows: North latitudes 33°-35°, 35°-37°, 37°-39°, and 39°-41°. They correspond roughly to the north Bermuda portion of the Central Atlantic warm water, the Gulf Stream and Cold Wall, the Slope-Water, and the Coastal Water, respectively, as described in our paper of 1933 above referred to (compare also the map accompanying Phil E. Church's paper in the present volume).

If the weather were influenced by the sea-temperature in a manner that would be useful in seasonal forecasting, the temperatures and precipitation of the middle and north Atlantic coasts in one month should show some relation to the sea-temperatures of the preceding month. For a first try, Boston and Baltimore were chosen, and to bring in no extraneous data only those months following months when sea-temperature data were available were used in making the averages and determining the departures.

What relation should we expect to find? The sea should have both a direct and an indirect influence on the coastal weather. The direct one should simply make the coast warmer and moister when winds blow onshore off a sea warmer than usual, and vice versa. The indirect effect works through the changes in general atmospheric pressure-distribution favored by departures of sea-temperature. When the sea is above normal in temperature, it will not only heat the air but also give it more vapor than usual. Such heated and humidified air is lighter than the average and so the atmospheric pressure is lower. The lower pressure over the sea favors northerly land-winds, both cool and dry, on the coasts to the northwest. So a warm sea should favor subnormal temperature and precipitation. Conversely, with the sea-temperature below normal the air would be denser, the pressure higher, and the wind consequently onshore from the south, bringing warmer and moister weather to the coasts. On the Atlantic seaboard, where the winds are prevailingly offshore, the direct influence must obviously be minor; therefore, the indirect should dominate.

The sequences of departures of weather and sea-temperature (Fig. 1) do not show any striking opposition, so we cannot say that the problem of seasonal weather-forecasting from ocean-temperatures is solved! On closer examination, however, the expected inverse relationship is found to predominate rather consistently. Obviously, with so many factors in control of our seasonal weather-abnormalities, the best we could expect would be that the trends of sea-temperature departure from month to month should have some effect on the trends of the weather. Nobody would claim that the excessively cold February this year was due to the Gulf Stream. Our North American weather-maps showed that the great masses of cold air came from Alaska and northern Canada, where the winter was also exceptionally cold (Charles H. Pierce, The cold winter of 1933-34, Bull. Amer. Met. Soc., March 1934). But it is reasonable to expect that a Gulf Stream warmer than usual would, by favoring lower pressures at sea, tend to increase the speed of flow of the arctic air and thus to make the winter colder than it would have been had the sea been a few degrees cooler and the pressure over it somewhat higher.

From Figure 1 the sequences of trends, whether upward, downward, or horizontal, were noted for each line. Then pairs of lines were compared as to sequences, by making tallies of the number of times the trend was upward or downward together against the number of opposite trends. In the cases of horizontal trends, that is, the departure one month the same as that of the preceding month, a half credit was given to both groups. If there were no relation and if there were a sufficient body of data,

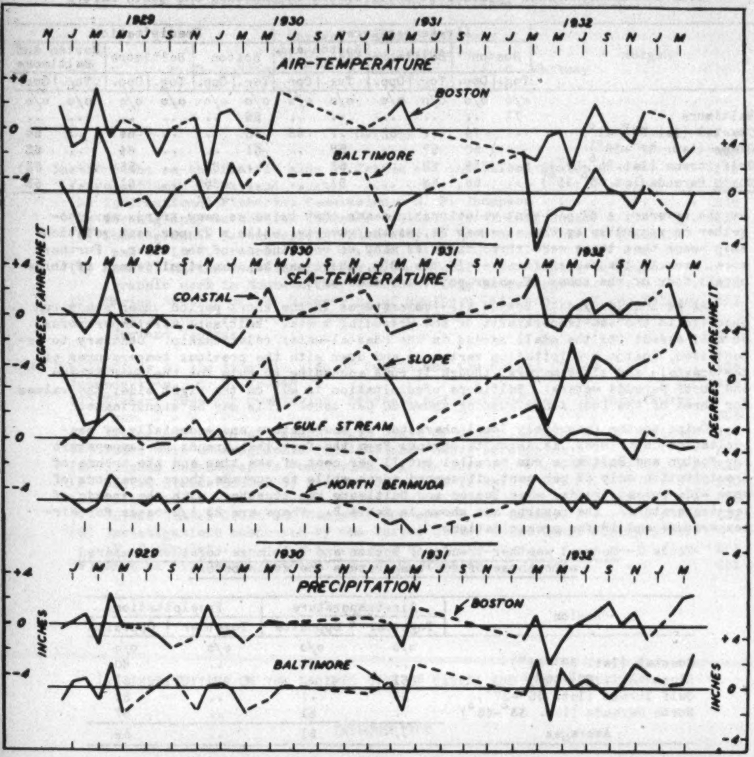

Fig. 1--Monthly sequences of departures of air-temperature and precipitation at Boston and Baltimore from December 1928 to April 1933, in comparison with those of sea-temperature by zones between New York and Bermuda from November 1928 to March 1933.

there should be as many trends together as opposite. If the relation were perfect, all trends of each pair of curves should be up or down together. The degree of relationship, whether together or opposite, is shown therefore by how much the percentage of either rises above 50 per cent and approaches 100 per cent, provided, of course, there are enough data. In the present sampling there are but 33 intervals which, while not adequate to establish relationships, may suggest lines for further investigation. Table 1 presents the results of the tallies, showing the percentages together or opposite.

None of the percentages in Table 1 is large. Perhaps all the deviations from 50 per cent could be explained by chance in this small body of data. Yet the values of 60 per cent or greater in Table 1 may have some claim to attention. A 60 per cent relationship means that the trends were together or opposite half again as many times

Table 1--Weather-trends relative to those of sea-temperature one month before

Region	Air-temperature						Precipitation					
	Boston		Baltimore		Boston and Baltimore		Boston		Baltimore		Boston and Baltimore	
	Tog.	Opp.	Tog.	Opp.	Tog.	Opp.	Tog.	Opp.	Tog.	Opp.	Tog.	Opp.
	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o
Baltimore	71	..	..	..	..	..	58	..	..	..	..	..
Coastal (lat. 39°-41°)	..	74	..	52	..	56	56	..	..	64	..	54
Slope (lat. 37°-39°)	..	50	67	..	58	..	61	..	..	64	..	52
Gulf Stream (lat. 35°-37°)	..	58	59	..	51	..	..	52	..	55	..	53
North Bermuda (lat. 33°-35°)	..	56	58	..	51	..	..	55	..	61	..	58

as the reverse; a 67 per cent relationship means that twice as many trends were together or opposite, as the case may be, as the reverse; while a 75 per cent relationship means that there were three times as many of one kind as of the other. Furthermore, even in the cases of values in the 50's, there may be some significance if three or all four of the zones of water point the same way.

As we should expect, Boston air-temperatures in the short period under study run opposite to the sea-temperatures of the preceding month. Baltimore air-temperatures do not, except for the small excess in the coastal-water relationship. Contrary to expectation, Boston precipitation varies up and down with the previous temperatures of the coastal- and slope-waters, though it runs according to rule for the Gulf Stream and North Bermuda waters. Baltimore precipitation is all on the right side, the values for three of the four zones running above 60 per cent. This may be significant.

Owing to the frequently local character of temperature and especially of precipitation-departures, as is quite obvious from the fact that trends of temperature for Boston and Baltimore run parallel but 71 per cent of the time and the trends of precipitation only 58 per cent, it seemed worth while to compare those occasions of more wide-spread trends, when Boston and Baltimore ran together, with the trends of sea-temperature. The results are shown in Table 2. There are 23 1/2 cases for air-temperature and 19 for precipitation.

Table 2--General weather-trends of Boston and Baltimore together compared with those of sea-temperature one month before

Region	Air-temperature		Precipitation	
	Together	Opposite	Together	Opposite
	o/o	o/o	o/o	o/o
Coastal (lat. 39°-41°)	..	68	..	60
Slope (lat. 37°-39°)	61	..	..	57
Gulf Stream (lat. 35°-37°)	55	..	..	52
North Bermuda (lat. 33°-35°)	..	51	..	67
Averages	..	51	..	59

Conclusions--From this sampling, it seems possible that the coastal waters may give indications of the air-temperatures of the following month along the middle and north Atlantic seaboard, low sea-temperatures being followed by high air-temperatures, and vice-versa. Furthermore, it seems likely that the precipitation stands in inverse relationship to the general sea-temperature of the preceding month. These are in accordance with what should be expected from the persistence and the indirect influence of sea-temperature departures acting on winds through atmospheric temperatures, humidities, and pressures. Further investigation seems worth while, especially of precipitation, though a seasonal separation of temperature might bring more striking results here also. More general indices to the sea-temperatures and to the weather can readily be compiled from data already in hand.

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REPORT OF THE COMMITTEE ON OCEANOGRAPHIC ACTIVITIES OF NORTH AMERICA DURING APRIL 1933 TO APRIL 1934

T. Wayland Vaughan, Chairman
C. O. Iselin, Secretary
E. D. Collins T. G. Thompson P. C. Whitney

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(A) INSTITUTIONS ON THE PACIFIC SIDE OF CANADA AND THE UNITED STATES

INTRODUCTION

T. Wayland Vaughan

In connection with the oceanographic activities on the Pacific side of Canada and the United States, some account should be taken of the oceanographic program at the Fifth Pacific Science Congress which was held under the auspices of the National Research Council of Canada in Victoria and Vancouver, B. C., June 1 to 14, 1933. There were given at this Congress about one hundred and fifty papers dealing with subjects definitely oceanographic or with subjects of significance for oceanographic research. Shortly after my return from the Congress about the end of June I prepared a "Report on oceanography at the Fifth Pacific Science Congress," had it mimeographed, and distributed it to about two hundred persons. The papers presented at the Congress were classified under six heads: (1) General status of oceanographic research in the Pacific; (2) sea-bottom configuration, hydrographic surveying, gravity-determinations, and the structure of the Earth's crust beneath the ocean-basins; (3) marine meteorology, dynamical oceanography, and chemistry of sea-water; (4) biology; (5) fisheries; (6) fisheries technology. One of the communications is the Report of the International Committee on the Oceanography of the Pacific, which gives a comprehensive account of the work done on the oceanography of the Pacific between May 1929 and June 1933. It contains notes on the principal expeditions, plotting sea-surface temperatures, studies of sea-bottom configuration, submarine earthquake-epicenters, marine bottom-deposits, oceanographic activities according to the different countries, corals and coral reefs of the Pacific, and a catalog of the marine stations of the Pacific. This report is now in type and should be ready for distribution in the very near future. The other papers will also be published in the Proceedings of the Fifth Pacific Science Congress.

[Note: Dr. Vaughan presented the Committee's report in person before the meeting of the Section of Oceanography of the American Geophysical Union, April 27, 1934. Included in the report is the substance of his two communications presented before the Section of Oceanography under the titles "The present status of oceanographic exploration on the Pacific" and "Oceanographic research in the Pacific institutions on the Pacific Coast of Canada and the United States during the past year."]

Scripps Institution of Oceanography,
University of California,
La Jolla, California

INTERNATIONAL FISHERIES COMMISSION

W. F. Thompson

The International Fisheries Commission, established for the preservation of the Pacific Halibut fishery and created by treaty between the United States and Canada, is the first body of its kind to be entrusted with the investigation and regulation of a depleted deep-sea fishery. Realizing that the feasibility of cooperative international control of a sea-fishery is on trial, it has proceeded carefully, conducting a thorough scientific study of the life-history of the halibut and of the condition of the fishery as a basis for regulation.

The investigations of the Commission have made it possible to understand the past history of the fishery, its decline, and the present depleted condition of the populations on many of the banks. Sufficient information regarding the fish and the fishery has been obtained to outline and make effective regulations designed to lead to the rehabilitation of the fishery. Active regulation has now been in effect for two years and has already improved the stocks on the banks.

Past experience in the regulation of other marine fisheries offers no information which makes it possible to predict the effect of regulation on this fishery and through it upon the halibut species. Each regulation must be regarded as an experiment and be given the same careful observation accorded any other experiment. The fishery is in a state of constant change, and its successful regulation requires a system of statistical and biological observations, by which old regulations may be judged and on which new ones must be based. Such a system was installed by the Commission on anticipation of active regulation and must be continued as long as the fishery is under control.

The statistics of the fishery form an indispensable part of the facts gathered. Those collected include not only the ordinary statistics of landings but also those of catch by bank of origin and by unit of fishing effort. Their collection and analysis are very laborious tasks but supply information that can be obtained in no other way. From them the changes in the intensity of the fishery and the changes in the abundance of fish are determined from bank to bank and from season to season.

Equally important are the biological studies. These are limited to the phases of the life-history that have a specific bearing on the problems of determining the condition and needs of the fishery and of devising methods for the rehabilitation of the stock. Fecundity, amount and distribution of spawning, larval development, drift of the pelagic eggs and larvae with the currents, rate of growth, size and age-compositions of the different stocks, migrations of the adults, and the existence of geographically distinct races are being investigated. Many facts of fundamental importance have been established, but many more await solution.

Of more general interest is the study of the ocean-currents along the coast by means of hydrographic sections and drift-bottles. A knowledge of these during the spawning season is essential for the determination of the drift of eggs and larvae. By means of hydrographic sections made during three winters, a general idea of the currents in the Gulf of Alaska has been acquired. Knowledge of currents along the outer coasts of southeastern Alaska and northern British Columbia is unreliable for the surface and lacking for the deeper water. These must be investigated as soon as possible.

During 1933, field-work, which involves the charter of a vessel suitable for operation in the open sea, was for financial reasons restricted to two and one-half months at the beginning of the year. Most of the work was done in the Gulf of Alaska off Yakutat, where spawning is still relatively abundant, and as far west as Kodiak Island. The geographical distribution of eggs and larvae, for comparison with that of past years, and the vertical distribution of the same, were investigated by means of qualitative net-hauls. Quantitative net-hauls, temperatures, and water-samples for salinity and oxygen-content were taken at different levels at a number of stations. Several hundred drift-bottles were also liberated. About March 1, 1933, a short trip was made to a small spawning bank off the coast of northern British Columbia, during which halibut were marked and liberated to determine the relation of the population there during the spawning season to those of the neighboring banks at other times of the year. Data relating to age and maturity were also collected.

The efforts of the Commission have already produced favorable results. The abundance of halibut on all the banks has definitely increased as a result of a reduction in intensity of the fishery. This is only a first step in the rebuilding of the fishery, but it offers reasonable assurance of the ultimate success of the Commission in the fulfilment of its purpose--the preservation of the halibut fishery.

International Fisheries Commission,
Seattle, Washington

OCEANOGRAPHY IN BRITISH COLUMBIA IN 1933

C. McLean Fraser

Most of the work on oceanography in British Columbia, in the first half of the year 1933, was centered around the program of the Fifth Pacific Science Congress, as several papers were prepared for presentation.

The investigation of fiords was completed, at least for the time being, and the final reports were presented. Dr. Neal Carter, who was in charge of this investigation, was appointed Director of the Fisheries Experimental Station at Prince Rupert. He entered upon his new duties towards the end of the year. Many of the phases of the physical, chemical investigation of the waters of the Strait of Georgia in the vicinity of Nanaimo and near the mouth of the Fraser River, that were to some extent associated with the work in the fiords, are being continued, more especially as this applies to the richness of phosphates. Quantitative examination of the plankton was continued.

The most important new development in physical and chemical oceanography during the year was the initiation of a closer cooperation between the work of the Hydrographic Survey and the Biological Board of Canada. A new, well-equipped survey-vessel, the Wm. J. Stewart, has recently been put into commission for work in the coastal waters of British Columbia. During the Congress cooperative plans were discussed by the Chief Hydrographer of the Wm. J. Stewart and the Director of the station at Nanaimo, with the result that a chemist from the station spent some time during the summer on the vessel, making use of the data obtained by the hydrographers, and obtaining physical and chemical data directly to go with these. This cooperation worked out so satisfactorily that it is to be continued and extended during 1934.

The major biological problems on salmon, trout, herring, pilchard, oysters, crabs, marine wood-borers, etc., are receiving continued attention. In several cases the field-work has been somewhat curtailed on account of the lessened budget, but there has been some compensation for this in additional work in the laboratory. Several of the assistants in these researches have gone back to the universities on leave of absence for the session in order to work up the material and data they have obtained in the field as a basis for the major thesis for the doctorate.

In connection with the faunistic studies, the general faunal check-list has been issued in book form by the National Research Council. It will be very useful for reference in almost every type of biological work that may be carried on along this coast.

Additional physical and chemical records are being taken to be used in connection with the work on marine wood-borers.

Fisheries Experimental Station, Prince Rubert, British Columbia--Much attention is still given to the study of the structure and chemical properties of fish oils and fatty acids and of the vitamin-potency of fish oils and other fish products. An investigation on preservation of nets is being continued and the problem of the effect of various conditions on the salting of herring is receiving attention.

Methods of decreasing or preventing the decomposition and discoloration of halibut in the holds of fishing vessels, as well as in cold-storage, are being developed satisfactorily. The study of an improved glaze, incorporating a germicide, for these cold-storage fish, promises good results. Improvements of methods of refrigeration in railway-cars are indicated.

More intimate cooperation in the work of the two biological stations in British Columbia, and of both of them with the laboratories of the National Research Council, is making it possible to obtain better use of the facilities afforded by each.

University of British Columbia,
Vancouver, British Columbia, Canada

OCEANOGRAPHIC LABORATORIES, UNIVERSITY OF WASHINGTON

T. G. Thompson and C. L. Utterback

The work of the Laboratories is conducted in three places: The main Laboratory situated on the shore of Lake Union on the University Campus; the Laboratory situated at Friday Harbor, Washington, which is on San Juan Island about eighty miles north of Seattle and east of Victoria, British Columbia; and on board the Laboratory research-boat, the Catalyst. The Laboratory at Seattle is in operation during the entire year. The Laboratory at Friday Harbor is in partial operation during the entire year but serves largely as a summer laboratory and as a base for the summer operation of the research-boat. This Laboratory, in addition to serving the needs of the staff and our students, has been used by many visiting scientists from different parts of the United States and Canada. Research is carried on in physics, chemistry, zoology, bacteriology, and botany.

Following are some of the general activities in which the Laboratories were engaged during March 1, 1933 to March 1, 1934.

(1) Tidal observations for the United States Coast and Geodetic Survey by Dr. Lyman D. Phifer were continued. The work has been facilitated by the installation of a standard tide-gage on the observation-pier at Friday Harbor.

(2) Observations on the total energy received by direct and reflected solar-radiations have been made continuously during the year at Friday Harbor. These observations were secured, in part, to further the solution of several problems in progress at the Laboratories and also in conjunction with the United States Weather Bureau as a part of the program for the International Polar Year, August 1932 to August 1933. (Prof. C. L. Utterback and Dr. Lyman D. Phifer)

(3) Clifford A. Barnes accompanied the 1933 Aleutian Island Expedition of the United States Navy and established a number of dynamical sections on each side of the Aleutian Ridge in the North Pacific and in Bering Sea. The waters of these regions were also studied for many of their chemical constituents.

(4) Physical, chemical, and biological observations were carried on throughout the year at Friday Harbor. (Dr. Lyman D. Phifer and Prof. Thomas G. Thompson, Dr. Martin Johnson, and Prof. Robert C. Miller)

(5) Cooperating with the United States Lighthouse Service, samples of water for chemical and biological analysis are being collected at regular periods by the lightships on Swiftsure Bank and Umatilla Reef. Temperature-, wind- and current-observations are likewise being sent to the Laboratories. (Dr. R. J. Robinson, Dr. Lyman D. Phifer, Prof. Robert C. Miller, and Prof. Thomas G. Thompson)

(6) During the year the research-boat Catalyst was engaged in an oceanographic study of Puget Sound and the Strait of Juan de Fuca. Three trips were made during the summer of 1933 off the continental shelves of Vancouver Island and the State of Washington.

(7) The entire staff attended and presented papers at the Fifth Pacific Science Congress held in Vancouver, British Columbia, in June 1933.

(8) The Director of the Laboratories attended the Congress of the International Union of Geodesy and Geophysics in Lisbon, Portugal, in September and later visited a number of the marine laboratories in southern Europe.

The specific work accomplished by the Laboratories during the past year is represented by 22 scientific papers, published or in course of publication, and by 13 other papers for which the experimental work has been completed and which are in preparation.

Papers published

(1) Variations in visible solar light. C. L. Utterback. Science, v. 77, 118, 1933.
(2) Light-penetration in the waters of the San Juan Archipelago. C. L. Utterback and J. W. Boyle. J. Opt. Soc. Amer., v. 23, No. 10, 1933.
(3) Light-penetration in the waters of Southeastern Alaska. C. L. Utterback. J. Opt. Soc. Amer., v. 23, No. 10, 1933.
(4) Measurement of submarine illumination. C. L. Utterback. J. du Conseil, v. 8, No. 3, 1933.
(5) Determination and occurrence of fluorides in sea-water. T. G. Thompson and H. J. Taylor. Ind. Eng. Chem., Anal. Ed., v. 5, 87, 1933.
(6) Lithium in sea-water. B. D. Thomas and T. G. Thompson. Science, v. 77, 547-548, 1933.
(7) Photometric investigations of Nessler reaction and Witting method for determination of ammonia in sea-water. R. J. Robinson and H. E. Wirth. Ind. Eng. Chem., Anal. Ed., v. 5, 417, 1933.
(8) Determination of silicon in sea-water. T. G. Thompson and H. G. Houlton. Ind. Eng. Chem., Anal. Ed., v. 5, 417, 1933.

Papers accepted for publication

(1) Submarine illumination. C. L. Utterback. Proc. Fifth Pacific Sci. Cong.
(2) Electrical conductivity of sea-water. B. D. Thomas, T. G. Thompson, and C. L. Utterback. J. du Conseil.
(3) Refractivity-chlorinity relations. C. L. Utterback, T. G. Thompson, and B. D. Thomas. J. du Conseil.
(4) Distribution of dissolved oxygen in the North Pacific. T. G. Thompson, B. D. Thomas, and C. A. Barnes. Chapter in James Johnstone Memorial Volume, Liverpool, England.
(5) The waters of the Puget Sound Region. R. J. Robinson and T. G. Thompson. Proc. Fifth Pacific Sci. Cong.
(6) Reporting of data in oceanographic chemistry. N. M. Carter, E. G. Moberg, T. Skogsberg, and T. G. Thompson. Proc. Fifth Pacific Sci. Cong.
(7) Observations on the spawning and development of some Pacific annelids. J. E. Guberlet. Proc. Fifth Pacific Sci. Cong.
(8) Recent advances in the knowledge of the parasites of the marine fishes of the Pacific. J. E. Guberlet. Proc. Fifth Pacific Sci. Cong.
(9) Diatom-periodicity of the San Juan Archipelago. L. D. Phifer. Proc. Fifth Pacific Sci. Cong.

(10) Some properties of kelp colloids. G. B. Rigg and B. Dunsford. Proc. Fifth Pacific Sci. Cong.
(11) Photosynthesis in red algae. R. Tschudy. Am. J. Botany.
(12) Observations on hydrogen-ion concentration and temperature of surface-waters of several seas. R. C. Miller. Proc. Fifth Pacific Sci. Cong.
(13) Report on the free ammonia, albuminoid nitrogen, and organic nitrogen in the waters of the Puget Sound Area during the summers of 1931 and 1932. R. J. Robinson and H. E. Wirth. J. du Conseil.
(14) Free ammonia, albuminoid nitrogen and organic nitrogen in the waters of the Pacific Ocean off the Coast of Washington and Vancouver Island. R. J. Robinson and H. E. Wirth. J. du Conseil.

Papers completed and ready for publication

(1) The determination and occurrence of manganese in sea-water. T. G. Thompson and T. W. Wilson.
(2) Report on distribution of phosphates in the Puget Sound Area. R. J. Robinson, T. G. Thompson, I. Igelsrud, and C. A. Barnes.
(3) Determination and occurrence of boron in sea-water. T. G. Thompson and I. Igelsrud.
(4) The spawning, life-history, and points of head-development of two species of Nereis. J. E. Guberlet and M. W. Johnson.
(5) Studies on the morphology of some trematodes from Puget Sound fishes. J. E. Guberlet and F. J. Kohlruss.
(6) The morphology and distribution of rajonchocotyle from Puget Sound skates. J. E. Guberlet and G. Ablan.
(7) Bacteriological examination of the interior of the pneumatocyst of Nereocystis. G. B. Rigg and B. S. Henry.
(8) Seasonal settlement of shipworms, barnacles, and other wharf-pile organisms in Puget Sound. M. W. Johnson and R. C. Miller.
(9) Flight of albatrosses and other sea-birds. R. C. Miller.
(10) Continuous phytoplankton-collection. L. D. Phifer.
(11) Vertical distribution of diatoms in the Strait of Juan de Fuca. L. D. Phifer.
(12) Permeability of cells and tissues of Nereocystis. G. B. Rigg.
(13) Absorption of daylight in the northeast Pacific Ocean. C. L. Utterback and W. Jorgensen.

[Note: The above report, under the title "The activities of the Oceanographic Laboratories of the University of Washington during the past year," was presented in person by Prof. C. L. Utterback before the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934.]

Oceanographic Laboratories, University of Washington,
Seattle, Washington

HOPKINS MARINE STATION, PACIFIC GROVE, CALIFORNIA--REPORT ON HYDROGRAPHIC WORK IN MONTEREY BAY IN 1933

Tage Skogsberg

The same program as in 1932 was carried out. In other words, seven stations located at selected points in Monterey Bay were visited, weather permitting, once a week.

In the course of the year the following data were taken: Temperature, 4054; Cl, 1147; SiO_2, 940; and PO_4, 894.

The results very strikingly substantiated those obtained during previous years. A synthesis of five years' data shows that the Monterey Bay region is characterized by a very marked as well as remarkable rhythm in the hydrographical phenomena. Each year begins and ends with a period dominated by the Davidson Current; during the spring and summer the upwelling phenomenon predominates; and during the fall the Japanese Current is the outstanding hydrographic feature. However, these three phenomena, the Davidson Current, the upwelling, and the Japanese Current, vary in intensity from year to year. Particularly, the last two are subject to striking variations. In some years the most characteristic water of the upwelling, having a temperature of 8° C, rises to a level within a few meters of the surface, while in other years this condition is not obtained. Likewise, the Japanese Current shows extraordinary variations. It appears to sway in and out from the coast. This variation in the distribution of the Japanese Current apparently occurs all through the year but it becomes particularly striking during the period around September when the Current normally is closest to the coast. On rare occasions the water of the Current at that time is forced into the Bay. Usually, however, only marginal water is forced in, water which has characteristics intermediate in nature between the Japanese Current and the "normal" coastal water of that period.

It should be noted, however, that within the year the hydrographic rhythm is constantly interrupted due to local, apparently meteorological, conditions; the wind in particular brings on marked changes.

On these variations there is superimposed a variability of a longer period. Thus, the last two years were distinctly colder than the previous years. Particularly was this true of 1933, the coldest year on record so far. In this year the average monthly surface-temperature was about 25 per cent of the total thermal range below normalcy. It may be interesting to note in this connection that these low temperatures apparently are connected with the fact that the California sardine did not penetrate as far north as usual and that, as a consequence, this species returned to the Monterey Bay Region earlier, about one month, than usual. This is another example of the close correlation between the hydrography and the commercial fisheries. Still another example falling in this category is that the albacore this year visited our waters hardly at all.

Just as in 1932, in 1933 the deep central channel of Monterey Bay apparently played but a subordinate rôle in the upwelling phenomenon. Also, the water between 900 meters and the upwelling stratum, about 300 to 250 meters, was characterized by a considerable coastwise movement.

We have now concluded the analysis of the conditions of the Bay proper. The main result, besides the discovery of the fundamental hydrographic rhythm of the region, is the establishment of the fact that Monterey Bay waters are but secondarily affected by local meteorological conditions. In other words, the phenomena usually occurring in temperate regions, such as the cooling of the waters in the winter and their warming in the summer, are not clearly expressed in Monterey Bay. The primary features of this Bay mainly reflect large-sized water-movements of the open ocean. Monterey Bay is nothing but a bowl into which the ocean-waters pour in and out. It has no local water, only transient. This transient water is present in the form of eddies constantly moving north or south, a movement caused by the coastwise drift of the oceanic water.

Our next step will be an attempt to investigate the regions outside the Bay.

Hopkins Marine Station, Stanford University,
Pacific Grove, California

MARINE STATION OF THE UNIVERSITY OF SOUTHERN CALIFORNIA

F. M. Baldwin

The major program of our Station has consisted of routine work in the direction of trawling and dredging, and classifying marine specimens. Some progress has been made in the direction of research-investigation, especially on the behavior of certain marine fishes to environmental conditions, and this work will continue for the balance of the year. In this work we have made an attempt to determine factors that contribute to the activity of fishes, such as volume of water, homogeneous groupings as contrasted to heterogeneous groupings, etc. A preliminary report of some of this work will shortly appear in "Science," and we hope by the end of the year to have considerable data which will furnish some basis for concrete deductions. It will be possible perhaps later to describe more explicitly some features of this work.

Marine Biological Station, University of Southern California,
Los Angeles, California

OCEANOGRAPHIC RESEARCH AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY

T. Wayland Vaughan

Improvements--During the past year, by means of funds contributed by R. P. Scripps and from the estate of Miss Ellen B. Scripps, the Scripps Institution of Oceanography has been able to replace the gasoline-engine on its boat *Scripps* with a Diesel engine, and to make numerous improvements. Now, living conditions on the boat are better than they have been before and the boat is equipped to do all of the ordinary oceanographic work to a depth of about 5000 meters. Henceforth, it will be possible to make expeditions to a distance of between five and six hundred miles offshore.

Expeditions and oceanographic data--During the past year, in addition to numerous short trips offshore from San Diego or La Jolla, one cruise was made on the *Scripps* from La Jolla to San Clemente Island, thence to Santa Catalina and Balboa, and back to La Jolla. A series of stations was occupied for various oceanographic purposes, one of which included the collection of core-samples of bottom-deposits for chemical and bacterial investigation. R. H. Fleming spent about three months aboard the naval vessel *Hannibal* in the Gulf of Panama and off the coast of Costa Rica. He assisted in making oceanographic observations and collecting water-samples at 127 stations. While aboard the vessel he made numbers of chemical analyses for oxygen and phosphate, and collected surface plankton-samples. A report on the results is in preparation. Roger Revelle was aboard the United States Coast and Geodetic Survey steamer *Pioneer* for ten days during July and assisted in making nine vertical sections for salinity and temperature off Point Arguello. He also made oxygen-sections at each station occupied and collected bathypelagic organisms to study the interrelations between the vertical distribution of zooplankton and the oxygen-content of the water.

The quantity of oceanographic data received at the Institution during the past year is given in Table 1.

Table 1--Oceanographic data received at Scripps Institution of Oceanography, April 1933 to April 1934

Source	Salinity	Water-temperature	Air-temperature	Wind
U.S. transports..........................	0	4333	769	4333
U.S. lighthouse-tenders..................	192	965	765	965
U.S. Coast and Geodetic Survey vessels	(273)^a	(273)	0	0
Scripps................................	(287)	(287)	0	0
Shore-stations from La Jolla to Scotch Cap..................................	2610	2610	365	1880
Grace Line vessels from Valparaiso to Central America.......................	0	1975	1975	0
U.S.S. *Ramapo* and *Hannibal*............	(1050)	(1050)	0	0
Supplementary data off Lower California, Central, North, and South America. *Velero III*, Mazatlan..........	118^b	173^b	0	101
Totals.................	4530	11,666	3874	7279
Grand total.. 27,349				

( )^a = sub-surface data; b = various depths

In addition to the data indicated in Table 1, the Institution has a sea-water thermograph installed on the U.S. Lighthouse-Tender *Lupine* and on the U.S. Naval Tanker *Ramapo*. Two of the three thermographs installed on Panama Pacific Line steamers plying between New York and San Francisco were provided by the Scripps Institution, and arrangements have been made to receive photostat copies of all of their records. A recording current-meter of the pendulum-type has been designed for use on the sea-bottom and an experimental model is under construction.

Physical oceanography and marine meteorology--Dr. McEwen continued his studies of vertical and horizontal circulation in the sea along and off the west coast of the

United States, making use of data on winds as a cause, and the distribution of temperature and salinity as effects, of circulation. The results of this investigation which has been a long-continued one have been submitted for publication. Dr. McEwen carried on investigations of the amount of water each storm supplies to a water-shed in connection with the California Forest Experiment Station at Glendora. It is expected that this project will be a long-continued one--ten or fifteen years. The investigations on seasonal weather-forecasting have been continued in spite of the very much-reduced financial support.

In connection with the investigations on sediments at the Scripps Institution, certain statistical problems have been studied and progress has been made in their solution. Some of these problems are closely related to the differentiation of species and sub-species by appropriate statistical treatment of the measured characters. A number of numerical tables have been prepared for convenience in application, and a valuable collection of references, abstracts, and reprints dealing with modern statistical methods has been made.

H. R. Byers continued his researches on the air-masses of the North Pacific and he has prepared an extensive paper which has been accepted for publication in the Scripps Institution Bulletin, technical series. He also completed the manuscript of an article entitled, "Equivalent temperature as a physio-climatic element."

Chemistry--The work in the Chemical Laboratory has largely dealt with substances and conditions in sea-water that have been previously investigated. The chlorinity, plant-nutrients, oxygen, and the various components of the buffer-mechanism have been determined on samples collected regularly at the Institution's Pier as well as on samples collected from various depths off the coast of Southern California by the boat Scripps.

In a previous report the Institution's investigation of the buffer-system or the hydrogen-ion regulating mechanism of sea-water has been mentioned. During the past year a paper on this subject has been completed, and within a few weeks will be published in the technical series of the Bulletin of the Scripps Institution under the authorship of Moberg, Greenberg, Revelle, and Allen.

Further laboratory-studies of some of the components of the buffer-system have been in progress throughout the year. For example, water-samples have been analyzed for boron and titratable base, including a series of surface samples collected by the U.S.S. Ramapo, between the California Coast and the Philippines, and several vertical series taken by Messrs. Fleming and Revelle on the Hannibal and Pioneer, respectively. It was found that for all the localities and all the depths represented the ratio of both boron and base to the chlorinity was practically constant.

A study of importance in comparing the results of determinations of titratable base or alkalinity obtained by different methods was carried out in cooperation with Dr. P. H. Mitchell of Brown University. The base-content of a number of sea-water samples was determined both by Dr. Mitchell's modification of Thompson and Bonnar's method, and by the direct titration-method used in this Laboratory. The results were found to agree within the limits of the errors of the methods.

Microbiology--Dr. C. E. ZoBell, in charge of microbiology at the Scripps Institution, reports that a large proportion of the bacteria in the sea are able to ammonify numerous substances. Five new species have been isolated which produce ammonia from low concentrations of urea in sea-water. Nitrosofiers and nitrifiers have been recovered with regularity from bottom-deposits in relatively shallow water, but similar methods have failed to reveal their presence at depths greater than 500 meters. Nitrate-reducers are encountered very infrequently and they are functional only under unusual conditions. Observations on the influence of temperature, organic matter, pH, redox potentials, and salinity on the activities of nitrifying and denitrifying bacteria indicate that in the sea the redox potential is perhaps the most important factor.

Analyses of over 40 bottom-deposit samples from depths to 1300 meters show the existence of a large and varied microflora which is clastically active against cellulose, starch, and proteinaceous substrates. Aerobes predominate, but the ratio of anaerobes to aerobes increases with the depth of the core-strata. The reduction potential of most of the cores approaches that of the hydrogen-electrode and *in vitro* hydrogen overvoltages may be produced due to microbial action. Sulphate-reducing bacteria are common in the mud-samples.

It has been found that while immediately following initial isolation marine bacteria have specific sea-water requirements, they are readily acclimatized to become physiologically indistinguishable from fresh-water species. At least 88 new bacterial types from the sea have been characterized.

Miss Esther C. Allen has noted that the usual sequence of events in the fouling of submerged surfaces is first the adherence of bacteria and kindred growths, followed by the attachment of barnacles, Bryozoa, hydroids, etc. Bacteria and, to a lesser extent, diatoms play an important rôle in the fouling of marine structures.

In collaboration with Nelson A. Wells, the etiological agent of a highly fatal infectious dermatitis of Fundulus parvipinnis and other marine fishes has been isolated and identified as Achromobacter ichthyodermis, n. sp., and a paper published on the results.

Phytoplankton--Prof. W. E. Allen has continued his studies of phytoplankton of the La Jolla region, devoting most of his time to the preparation of the manuscript of a report on the results of ten years of daily collection at the end of the Institution Pier. Professor Allen has continued studies of fouling organisms along the lines initiated several years ago by Prof. Wesley R. Coe of Yale University. Miss E. E. Cupp has completed a manuscript entitled "A critical study of certain distinguishing characters in three closely allied plankton species of the diatom genus Nitzschia and their relations to certain environmental conditions." Miss Cupp has also prepared a report on the plankton-samples collected by the Velero III between San Diego and Panama.

Foraminifera--T. W. Vaughan during the year published a number of papers on fossil foraminifera. A publication of the Scripps Institution Bulletin, technical series, entitled "The temperature- and depth-distribution of some recent and fossil foraminifera in the Southern California Region" is one of significance both to students of the ecology of marine organisms and to geologists. During the year Earl Myers succeeded in completely working out the life-history of a local species of foraminifera known as Patellina corrugata. A short note entitled "Multiple tests in the foraminifera" was published in the Proceedings of the National Academy of Sciences (v. 19, No. 10, pp. 893-899, 1933). The complete report is now ready for publication and the results have been presented by Prof. C. A. Kofoid at the recent meeting of the National Academy.

Physiology of marine invertebrates--Notes on the work done during the past year are as follows. During the last twelve-month period an investigation has been made by Dr. D. L. Fox and Dr. G. W. Marks on the digestive enzymes of the plankton-feeding Mytilus californianus, with a view to determining the food that it can utilize and must remove from the sea. Its fecal ribbons have been examined for correlative information. The findings from these investigations will be correlated with Buley's studies of the gastric contents and Miss Austin's studies of other features of this mollusk. Studies on the effect of oxygen in the inactivation of catalase are being continued, using a number of marine animals and plants. A paper dealing with the subject entitled "The inactivation of mussel catalase by oxygen" appeared in the Journal of Biological Chemistry (v. 103, p. 269, 1933).

Another investigation in progress is concerned with the amounts of dissolved copper in sea-water, the tolerance of a number of marine mollusks for this toxic action, and the possible accumulation of it by the animals.

The mussel has in its digestive tract an enzyme or enzymes capable of hydrolyzing the poisonous glucoside amygdalin, with the production of a reducing sugar (glucose) and free hydrocyanic acid. Out of 69 bacteria, six actinomyces, three molds, and two yeasts investigated, two-thirds of the bacteria, and all the other forms excepting one of the yeasts, possess the ability while living to produce HCN from amygdalin. The mussel enzyme hydrolyzes amygdalin in the absence of microorganisms. A paper dealing with the subject has been prepared.

In cooperation with Dr. F. B. Sumner an investigation of considerable length concerning the carotenoid pigments in certain marine fishes has been completed and published under the title "A study of the variations in the amount of yellow pigment (xanthophyll) in certain fishes and of the possible effects upon this of colored backgrounds" (J. Exp. Zool., v. 66, p. 263, 1933).

During the year seven articles have been published from the section of physiology, two are in press, another has been prepared for publication, and three are in the process of preparation.

Fish-biology--The work in fish-biology consisted in a continuation of studies of the relations of marine fishes to their environment. The chief subjects of investigation were as follows: (1) The yellow (carotenoid) pigment of fishes, which is partly responsible for the striking adjustments of these animals to the color of their surroundings in nature, was investigated by Dr. Sumner, in cooperation with Dr. Fox of the physiology section.

(2) Studies were carried out by Dr. Sumner upon the relations of different parts of the visual field to the color responses of fishes. A new technique was devised, whereby the animals were forced to look through transparent caps which were fitted over the eyes, these caps being variously colored or partly obscured by opaque areas.

(3) Investigations of the oxygen-consumption of fishes were continued by N. A. Wells. The relations of the metabolic rate to activity, temperature, season, size, sex, and some other factors were determined in part, and certain phases of the work were brought to a definite conclusion.

(4) Certain diseases of fishes were investigated by Mr. Wells in collaboration with Dr. ZoBell of the section of microbiology, as has already been stated.

Marine bottom-deposits--During the year two rather large undertakings have been brought to completion. One of them is the study by E. M. Thorp entitled "Calcareous shallow-water marine deposits of Florida and the Bahamas," and the other is an investigation by Roger Revelle on the deep-sea bottom-samples collected by the Carnegie. These two investigations will merely be mentioned here, as it is intended to submit abstracts of the results obtained for inclusion in the report of the Committee on Sedimentation, Division of Geology and Geography, National Research Council. During the year much attention has been paid by several members of the staff of the Institution to oxidation and reduction in the ocean. This subject is a meeting ground of oceanography, geology, chemistry, and a considerable range of biological phenomena; therefore, the members of the staff of the Institution representing each one of these sciences have cooperated in the investigation.

Dr. Robley D. Evans, assisted by Arthur Kip, is making a study of the radioactive substances in sea-water and in the bottom-deposits off the coast of Southern California. They are also making similar analyses of core-samples of deep-sea sediments kindly supplied by Dr. Ph. H. Kuenen from the collections made by the Willebrord Snellius in the East Indies, and by the Hydrographic Department of the Imperial Japanese Navy obtained by the vessel Mansyu in the southwest part of the North Pacific.

Scripps Institution of Oceanography, University of California,
La Jolla, California

(B) INSTITUTIONS ON THE ATLANTIC SIDE OF CANADA AND THE UNITED STATES

INTRODUCTION

C. O. Iselin

This section of the report is confined mainly to the physical investigations in progress during 1933. Information has been received from the following major institutions located on or near the Atlantic seaboard: (1) Fishery Research Commission, Newfoundland; (2) Biological Board of Canada; (3) Woods Hole Oceanographic Institution; (4) Bingham Oceanographic Foundation; (5) United States Bureau of Fisheries; (6) United

States Hydrographic Office; (7) United States Coast and Geodetic Survey; (8) United States Coast Guard; and (9) Bermuda Biological Station. The detailed reports for the United States Hydrographic Office, Coast and Geodetic Survey, and Coast Guard were presented to the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934, and are printed above in the present volume of "Transactions."

In addition, there are of course a number of smaller laboratories primarily engaged in biological and physiological researches. These include the Mt. Desert Biological Research Laboratory, the Isle of Shoals Biological Station, the Department of Oceanography at Harvard University, and the St. Lawrence Biological Station of Laval University. This last institution has recently undertaken an extensive hydrographic and chemical survey of the waters of the mouth of the St. Lawrence River. Special mention should also be made of the recently organized Chesapeake Biological Laboratory at Solomons Island, Maryland, under the direction of Prof. R. V. Truitt. Another important oceanographic event of the past year was the First Johnson-Smithsonian Deep-Sea Expedition. Under the direction of Dr. Paul Bartsch, this Expedition brought back an extensive biological collection from the neighborhood of Mona Passage in the West Indies. About 160 deep sonic soundings were also secured from the Nares Deep and two hydrographic stations were occupied.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

FISHERY RESEARCH COMMISSION, LABRADOR AND NEWFOUNDLAND

Harold Thompson

Temperature- and salinity-stations--During 1933, 126 temperature- and salinity-stations, continuing the regular research-stations from 1932, were occupied, water-samples being taken from the surface to varying depths, the greatest of which was 400 meters. The area covered was from Hamilton Inlet, Labrador, in the north, around the Coast of Newfoundland, and over the Newfoundland Banks, with five stations on the Nova Scotia banks. This area is practically the same as that shown in Figures 1 to 10 at the end of our Annual Report for 1932.

Besides these regular research-stations, ten stations were made on the south of Grand Bank and 27 on Sable Island Bank, on commercial fishing-cruises of the Cape Agulhas in the early spring.

Drift-bottle returns--Four hundred and eleven drift-bottles were liberated over this area, and of this number 26, or 6.3 per cent, were recovered, all having drifted ashore on Newfoundland or adjacent coasts. Records of seven others liberated in the same area in 1932 were received from Norway, Faroe, Shetland, Ireland, and the Azores. It is noteworthy that no bottle liberated in 1931 drifted across the Atlantic, according to absence of returns.

Plankton-tows and trawls--At most of the hydrographic stations, hauls of different kinds were made and the following is a list of the total hauls of each kind: Plankton-nets--Vertical cheese (1-meter), 16 hauls between 25 and 100 m; vertical Hjort (27-inch), 121 hauls between 25 and 125 m; horizontal cheese-cloth, 101 hauls between surface and 75 m; and 2-meter ring-net, horizontal, 118 hauls between 15 and 100 m. Trawls--Vigneron-Dahl patent trawl, 24 hauls on the bottom between depths of 36 and 200 m; squid trawl, one haul (mid-water) at 25 m; otter trawl, five hauls, as Vigneron-Dahl. At two stations off Labrador cod were tagged.

Salmon-catches and physical conditions at sea--The correlation of the catches during the salmon-run on the northeast and southwest coast with the conditions prevailing in the sea was continued, and compared with the data obtained in 1932. It was found, on the whole, that in 1933 the temperature-conditions were favorable to the salmon-run, although the suitability, in the east and north, was late in occurring on account of the presence of so much ice, and was restricted in extent especially on the southeast, owing to a rapid change over to warmer conditions on the disappearance of the ice.

Records were kept of the temperature-conditions and the catches of salmon at Bay Bulls to ascertain the nature of the run there. This was found to be made up of typical small summer fish with an occasional grilse at first and latterly wholly of grilse. The commencement of the run and the time of maximum catch were found to be later in 1933 than in 1932, due to the colder conditions prevailing in the former than in the latter year.

Distribution of cod eggs and larvae in 1933--The distribution of these did not vary much from that of 1932 (compare Annual Report, 1932), although both eggs, and larvae and fry were carried further north through the Straits of Belle Isle in 1933 due to the diminution in the Arctic Current and the increase in the Arctic inflow through Cabot Strait. In the fall the fry were not distributed over the northern Grand Bank as in 1932, but were confined to the channels between the Banks in the track of the reduced Arctic Current. The eggs in 1933 were found to be at a more backward stage than those of 1932, probably on account of the lower temperatures prevailing.

Correlation of cod-catches with physical conditions remains to be completed. It is noteworthy that the run of squid, depended on for bait, was a failure. No obvious reason could be shown for this; it was possibly due to poor breeding season off continental shelf of America.

Fishery Research Commission,
St. John's, Newfoundland

BIOLOGICAL BOARD OF CANADA, EAST COAST OF CANADA, 1933

A. G. Huntsman

During the summer of 1933 the Biological Board of Canada repeated the oceanographic observations made in the Halifax area in 1932. The work was both started and completed somewhat earlier than in the latter year, extending from May until the beginning of September. The observations in August corresponded as exactly as possible in time with those made in the first year, so as to comply with the wishes of the international organization that planned the Polar Year of 1932-1933.

Ten stations forming two sections from Sambro Bank north-northeast and northwest respectively to the coast were occupied monthly, and in August an additional three stations completed a section across the channel between Sambro and Emerald banks. Six stations in a series from Bedford Basin through Halifax Harbor to the nearest point in the deep water of the Scotian Basin were occupied weekly.

Temperature-observations and salinity-samples were taken at each station at standard depths, and also for a fair proportion of the stations and depths samples were obtained and analyzed for phosphate-content. A limited number of oxygen-determinations were also made at these stations.

Several series of temperature-observations and salinity-determinations were made in Passamaquoddy Bay and adjacent estuaries in order to follow the effect of a freshet discharged through an estuary.

Deep tidal mixing has been seen as an important factor in effecting differential movements in the various layers of adjacent stratified water. Experiments to elucidate these movements were performed in a laboratory tank, and gave corroboration of results obtained in current-measurements in Passamaquoddy Bay. The effect of wind on the movements and also the somewhat different movements resulting from the addition of fresh water at the mixing point were also studied.

The shallow estuaries and bays of the Prince Edward Island Region are entirely covered with ice throughout a long winter season. Observations have been made through the ice in an estuary emptying into Malpeque Bay in order to trace the effect of the entering fresh water on both temperature and salinity during this winter period, when the action of wind and to a certain extent that of light are eliminated.

Biological Board of Canada,
Toronto, Canada

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Henry B. Bigelow

During the year 1933 the Atlantis cruised 17,600 miles and occupied 456 stations, the most important of which were distributed as follows: Bermuda to Nassau Section, 15 stations; Caribbean survey, 124 stations; four Florida-Current sections, 32 stations; and Gulf of Maine surveys (five cruises), 245 stations.

Besides the temperature-, salinity-, and oxygen-observations, a full chemical program was carried through at the great majority of stations. The routine chemical determinations consisted of pH, PO_4, NO_2, and NO_3. At a number of points ammonia and boron were also observed.

While engaged in this work about 770 deep sonic-soundings were taken including three sections across the Bartlett Deep. Bottom-samples were collected at two-mile intervals from the coast to deep water on the four sections across the Florida Current. About 25 mud-cores were taken between Bermuda and Woods Hole.

The more specialized physical observations carried out during the past year on board the Atlantis include light-intensity investigations and evaporation-measurements.

Laboratory investigations of the Woods Hole Oceanographic Institution

Henry B. Bigelow--Physical oceanography of the waters on the Continental Shelf, Cape Cod to Chesapeake Bay. (Published as Contribution No. 34 of the Institution.)

Phil. E. Church--Studies of the distribution of surface-temperature in the western North Atlantic, based on thermograph-records. Twenty additional synoptic charts were prepared. The area has been further extended to include all of the North Atlantic west from a line between Halifax and Cape San Roque. (For an account of this work see paper presented by Phil. E. Church before the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934, and printed in the present volume of "Transactions."

George L. Clarke--The penetration of the blue component of daylight into the waters of the Gulf of Maine was measured in the course of a study of the diurnal migration of the zooplankton.

C. J. Fish--Oceanographic program sponsored by the International Passamaquoddy Fisheries Commission. The following physical investigations have been completed, based on field trips covering the period July 1931 to September 1932: (a) The annual temperature-cycle at the surface; (b) the horizontal distribution of temperature at different levels for each cruise; (c) the surface-circulation and rate of drift as indicated by 106 drift-bottle returns.

Columbus Iselin--Studies based on Atlantis deep-sea temperature- and salinity-observations. A general report on the circulation of the Western North Atlantic has been nearly completed, the Atlantis observations of 1933 having been added to the results of the two previous years.

Ancel B. Keyes--Studies on dissolved organic substance and ammonia in the sea. Ammonia values ranging from 0 to 60 mgs. NH_3 - N per cubic meter were found in the systematic study of 130 water-samples from 22 stations in the Gulf of Maine. A technique suitable for work at sea was perfected.

A. Krogh--Studies on organic matter dissolved in sea-water and present in bottom-samples. It was shown experimentally that at most a small fraction of the organic material can be present in a colloidal state, at least 90 per cent being in true solution. Bottom-samples were taken from the surface-layer of the mud at depths of from 1000 to 5000 meters. The values for organic material per gram of dry mud ranged from 16.1 mg.C and 5.0 mg.N to 4.4 mg.C and 1.7 mg.N. At depths of 7 to 15 cm in the bottom-mud the percentage of organic material was appreciably less.

Robert H. Oster--Penetration of red light into the sea. Measurements of the intensity of daylight in the red region of the spectrum (6000 to 7000 Ångstroms) on deck and at depths down to 30 m were made in the Gulf of Maine Region. Observations showed that red light decreased to one per cent of its over-surface intensity at 12.5 m in the Gulf of Maine and 7 m in Woods Hole Harbor. It was also found that the transmissive exponent for light of these frequencies was approximately 3.5 times that for blue light.

Norris W. Rakestraw--Studies on the chemistry of sea-water. A beginning was made of an intensive chemical survey of the Gulf of Maine in an effort to get data covering the seasonal variations of phosphate, nitrate, pH, and possibly buffer-capacity. Samples were collected for work on boron, iron, and copper.

Alfred C. Redfield--Studies in biological chemistry. (a) The proportions in which the quantities of nitrate, carbonate, phosphate, and oxygen occur in different samples of water from the open ocean was found to be governed strictly by the composition and quantity of plankton which have decomposed in the water in question. (b) In connection with the chemical survey of the Gulf of Maine, a great many oxygen-determinations have been made which will prove an important aid in working out the details of the circulation in this region, as well as in the physiological problem.

C. G. Rossby--Investigations in meteorology and physical oceanography. (a) The theoretical investigation of the homogeneous surface-layer of the ocean has been continued. (b) A baro-thermograph for accurately recording the vertical temperature-distribution within this layer (0 to 200 meters) has been built.

H. R. Seiwell and Gladys E. Seiwell--Studies of phosphorous- and oxygen-content of the western North Atlantic basin. (a) A report on the horizontal, vertical, and seasonal variations of oxygen in the western North Atlantic has been completed. (b) A report on the nutrient phosphorous-content of the same area is well advanced.

H. C. Stetson, Marshall Schalk, and C. W. Taylor--Studies in sedimentation and sedimentary environments. (a) At four points between Cape Canaveral, Florida, and Cape Hatteras, bottom-samples were secured along lines extending from the shore out to deep water. This completes the traverses, eleven in all, which were planned as a survey of the sediments of the Atlantic coast. The data has all been compiled and a report is in progress. (b) The bottom-cores obtained in the arctic by the Nautilus were analyzed and a report published. (c) Direct observations on the rates of transportation and deposition of sediments were made at nine stations.

E.E. Watson--Hydrography of the Bay of Fundy. The investigations of the International Passamaquoddy Fisheries Commission left a considerable quantity of hydrographic material to be examined in further detail. A final report should soon be completed.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

BINGHAM OCEANOGRAPHIC FOUNDATION

A. E. Parr

During 1933, the main activity in the field of physical oceanography has been centered around a hydrographic and chemical survey of the Caribbean Sea. This was a joint undertaking with the Woods Hole Oceanographic Institution and has been continued with a two months cruise during the winter of 1934.

In cooperation with the United States Bureau of Fisheries, 164 surface temperature- and salinity-stations were also made in Delaware Bay and along the southern coast of New Jersey.

The recent publications of the institution include a report by Dr. A. E. Parr entitled "A geographic-ecological analysis of the seasonal changes in shallow water along the Atlantic Coast of the United States."

Bingham Oceanographic Foundation, Yale University,
New Haven, Connecticut

UNITED STATES BUREAU OF FISHERIES

Frank T. Bell

The main oceanographic activities of the United States Bureau of Fisheries during the past year are briefly summarized in the following paragraphs.

(a) Cruise of the Phalarope II, June 3-7, 1933--In the general locality of Eastern Long Island, 32 temperature-stations were occupied.

(b) Cruise No. 16 of the Atlantis, June 19-30, 1933--In the southern half of the Gulf of Maine, 48 temperature- and salinity-stations were occupied and a number of lines of drift-bottles set out.

(c) Near Milford, Connecticut, in Long Island Sound--Four very complete stations were made at which the following observations were made: Temperature, salinity, hydrogen-ion concentration, phosphates, copper, and iron.

(d) South Atlantic and Gulf oyster investigations--(1) North Carolina, 16 stations; (2) South Carolina, 7 stations; (3) Georgia, 3 stations; (4) Florida, 69 stations; (5) Louisiana, 14 stations. At all of these stations temperature, salinity, and pH were observed and at many of them the copper-content as well.

(e) Shrimp investigations along the Southern Atlantic Coast--(1) Surface-temperature and salinity were obtained at 234 stations and (2) surface- and bottom-observations were obtained at 72 stations.

(f) Louisiana shrimp investigations--Surface- and bottom-observations were obtained at 220 stations.

(g) Inshore trawling stations, Delaware Bay and New Jersey Coast--At 164 stations surface-temperature was observed and at many of these salinity as well.

U. S. Bureau of Fisheries,
Washington, D. C.

UNITED STATES HYDROGRAPHIC OFFICE

W. R. Gherardi

The report on "The oceanographic activities of the Hydrographic Office and the United States Navy during April 1933 to April 1934" was presented in person before the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934. It is printed in full with the proceedings of that Section in the Transactions of the Fifteenth Annual Meeting of the Union.

U. S. Hydrographic Office,
Washington, D. C.

UNITED STATES COAST AND GEODETIC SURVEY

R. R. Lukens

The oceanographic work of the United States Coast and Geodetic Survey is reported upon in the communication "Oceanographic activities of the United States Coast and Geodetic Survey" by R. R. Lukens, which was presented at the meeting of the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934. That communication is printed with the proceedings of the Section in the Transactions of the Fifteenth Annual Meeting of the Union.

U. S. Coast and Geodetic Survey,
Washington, D. C.

INVESTIGATIONS CONDUCTED BY THE UNITED STATES COAST GUARD DURING 1933

H. G. Hamlet

During the Ice-Patrol season of 1933 the United States Coast Guard Patrol-Boat General Greene made six cruises in the vicinity of the Grand Banks of Newfoundland, collecting on each cruise, by observation and radio reports, data for the construction of surface isothermal charts of the Grand Banks Region. During this period 25 oceanographic stations were occupied, at each of which temperatures and salinities were measured from the surface down to 1000 meters where the depth permitted. About 100 fathometer-soundings for which positions and correction-data are available were taken, chiefly in the rectangle between 46° and 48° north latitude, and between 45° and 48° west longitude.

A post-season northern cruise was made in the waters between Newfoundland and Labrador, and southwestern Greenland between June 26 and July 24, 1933. One hundred and twelve oceanographic stations were taken, most of them being reoccupations of stations taken on the northern cruise in 1931. At these stations temperature- and salinity-measurements extended from the surface down to 2000 or 2500 meters where the depth permitted. Several hundred well-located fathometer-soundings were taken for which correction-data are available. Arsuk Glacier in southwestern Greenland was visited and photographs recording its retreat were made.

The results of the work of the season of 1933 will be published in the United States Coast Guard Bulletin 23, and the data collected on the post-season cruise will be published along with the results of the northern cruise in 1931 of the General Greene and the Marion Expedition of 1928 in United States Coast Guard Bulletin 19, part 2.

Publication relating to oceanography issued during 1933 was United States Coast Guard Bulletin 22 (International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1932).

[Additional details regarding the Coast Guard's activities were prepared for the Section of Oceanography of the American Geophysical Union at its meeting April 27, 1934, by R. M. Hoyle under the title "The oceanographic work of the International Ice Patrol and Ice Observation Service carried on by the Coast Guard in 1933." In the absence of the author, the paper was read by E. M. Webster. It is printed in full above in the proceedings of the Section in this volume of "Transactions."]

BERMUDA BIOLOGICAL STATION

J. F. G. Wheeler

Drift-bottle work--Nineteen trips were made in the course of the year during which 361 drift-bottles were released in an effort to discover the surface-currents round the islands. On three of these trips an almost complete circuit of the islands was made, the remainder being done either just before or just after the long trip. Twenty-six bottles were washed ashore or picked up round Bermuda but none has been reported elsewhere.

This work was started in 1932 and has proceeded up to date. The total releases number 499 and the returns 36. Positions are plotted from two- or three-point bearings taken with a prismatic compass and the resulting drift has been charted in periods of three months.

Temperatures--Surface-temperatures only have been taken owing to lack of gear. These correspond with the drift-bottle trips together with half a dozen observations made during plankton-hauls and some isolated readings by independent workers. No salinities have been taken except for special purposes by independent workers.

Tide-gauge--The self-recording tide-machine installed on a jetty in the "Reach" has functioned through the year with the exception of a period in February when the clocks had to be replaced. The tide-rolls are sent to Washington and photostat copies of the records are filed at the Station.

Biological work--Plankton-hauls are made every month and during the drift-bottle trips. A fine net has been used at the surface, at 50 m, and at 130 m, which is the limit of the gear. A coarse one-meter net has also been used with little success. This work has been limited to four or five miles from the islands.

A fauna list of shore-invertebrates is being built up, with the times of breeding, and the Sargassum weed fauna has also been studied.

Bermuda Biological Station,
Hamilton, Bermuda

AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF VOLCANOLOGY

Washington, D. C.
April 26, 1934

REPORTS AND PAPERS

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RARE CHEMICAL CONSTITUENTS OF AMELIA (VIRGINIA) PEGMATITE DIKES, AND THEIR MINERAL SOURCES

Jewell J. Glass

(Published by permission of the Director, United States Geological Survey)

Students of igneous phenomena have long since become familiar with the occurrence of rare minerals in pegmatitic bodies. The great local concentration of rare elements in pegmatite minerals provides a remarkably good opportunity for the investigation of deep-seated rock constituents, for it is reasonable to suppose that these same elements are widely distributed in minute amounts through the parent rocks to which they are genetically related; but their concentration in pegmatite bodies affords a record of their presence that is lacking in other rocks.

The unusual number of rare minerals of the Amelia, Virginia, pegmatites has long attracted attention, and the rare elements of the more abundant minerals which have been investigated in the laboratories of the United States Geological Survey afford an unusual opportunity to study the rare constituents of a pegmatite. This famous locality for rare minerals is situated 38 miles southwest of Richmond, just south of Appomattox River, on the Piedmont plateau.

Minerals containing rarer elements including rare-earths, shown by chemical analysis

Allanite (orthite), the rare-earth epidote, occurs in tabular or bladed crystals from 5 to 15 inches long. It is a mineral containing the cerium group of rare-earths--lanthanum, cerium, and didymium--totaling 21 per cent of its composition.

Monazite, the cerium phosphate, is found mostly in crystalline masses, some of which weighed eight pounds. Monazite has the greatest concentration of rare-earths of any of the minerals examined; 50 per cent of its total composition being cerium metals alone. Seventy per cent of the total composition consists of rare constituents. The thorium-content is unusually high. Of 19 analyses of monazite from different parts of the world the Amelia mineral shows the highest ThO_2-content--18 per cent as compared with an average of about eight per cent for the others.

Mangano-tantalite, also called columbite, is a tantalate rich in manganese. In the upper portion of the deposit the material is iridescent black; at the lower levels it becomes dark red in color and shows a marked increase in specific gravity. This mineral occurs in considerable abundance in both mines. Mr. Morefield reported that he had taken 114 pounds from a ten-foot working in the mine last summer. Crystalline masses four and one-half inches thick and five inches long were reported as being common in the Rutherford mine. The rare elements present in this mineral are columbium and tantalum, which make up 84 per cent of the composition--31 per cent columbium and 53 per cent tantalum.

Microlite, a calcium tantalate, one of the rarest and most remarkable of all pegmatite minerals, occurs in fine octahedral crystals up to one inch in diameter and crystalline masses that weigh four pounds. Microlite represents the greatest variety of rare elements that is known to exist in the Amelia pegmatite minerals. There are 15 chemical constituents reported in the analysis of this mineral, seven of which are rare elements. Sixty-eight per cent of the total composition is tantalum. Microlite is the only member of this rare-earth group found to contain uranium and tungsten. The olive-colored variety of microlite is strongly radioactive; the amber variety gives a negative response, as observed from tests made in a gold-leaf electroscope.

Helvite is a manganese silicate containing eleven per cent beryllium and carrying iron and sulphur as minor constituents.

Zircon occurs sparingly in small clusters of elongated radiating wood-brown crystals and contains 63 per cent ZrO_2.

The radioactive elements present in this group of minerals are thorium, which constitutes 18 per cent of monazite, and uranium, 1.59 per cent of microlite.

Other rare-earth minerals--pyrochlore, fergusonite, hatchettolite--have been reported but not confirmed.

Table 1--Rarer elements including rare-earths in Amelia (Virginia) pegmatite minerals shown by chemical analysis

Name of mineral	Mine[a]	La_2O_3	Ce_2O_3	Di_2O_3	$(Y,Er)_2O_3$	BeO	ZrO_2	Nb_2O_5	Ta_2O_5	WO_3	ThO_2	UO_3
Allanite (Orthite)	R	3.47	11.14	6.91	....	....	....	....	....	....	....	....
Monazite	R,M	10.30	16.30	24.40	....	....	....	....	....	....	18.60	....
Mangano-tantalite (Columbite)	R,M	....	....	....	....	....	....	31.40	53.41	....	....	....
Microlite	R,M	....	....	0.17	0.23	0.34	....	7.74	68.43	0.30	....	1.59
Helvite	R	....	....	....	....	11.00	....	....	....	....	....	....
Zircon	R,M	....	....	....	....	....	63.00	....	....	....	....	....

[a] R = Rutherford Mine; M = Morefield Mine.

Spectrum-analysis of rarer elements in pegmatite minerals of Amelia, Virginia

Spectrum-analysis is being widely adopted in mineralogical laboratories as an accessory means of identification of mineral species and for the investigation of the rare elements in their composition.

Spectrum-analysis by the photographic method was made by George Steiger of the United States Geological Survey on 28 mineral specimens from Amelia, Virginia. Mr. Steiger tested each specimen for only eight metals--copper, lead, bismuth, tin, zinc, germanium, beryllium, and boron. Tests were made by placing finely ground material directly in the arc, without preliminary concentration by chemical treatment; the tests are accurate to 0.02 or 0.03 per cent, probably larger for copper.

The graphite electrode contains sufficient copper to give two persistent lines, and unless other copper lines were visible copper was not reported as present.

Tests were made, after concentration, on four specimens for rubidium, lithium, potassium, and caesium. Two samples of amazonstone--one from each mine--and the zinnwaldite show rubidium, lithium, and potassium, but no caesium. The topaz shows none of these metals.

Twelve of the samples contain boron; without an exception all the micas contain boron--both the sericites and the muscovites--as well as the zinnwaldite. Boron occurs also in oligoclase-albite, phenakite, and tourmaline.

Nearly half of the samples tested show the presence of beryllium. This would indicate a wide distribution of beryllium. Beryl, the most common source of BeO, occurs in large crystals and contains 13 per cent BeO by chemical analysis. The mineral richest in beryllium, however, is phenakite. Phenakite occurs in small individual quartz-like crystals and in cleavage pieces one and one-half inches long at the Morefield mine, and contains 45 per cent BeO.

Copper occurs "doubtful" in beryl and spessartite.

Germanium, up to recent time, was known in few associations. As a matter of fact, it has wide distribution. Germanium appears to be a characteristic constituent of topaz. In a compilation of spectrum-analyses by Fitch of London, topaz from 38 localities of different parts of the world contained germanium. Fifteen samples of topaz have been examined by Mr. Steiger and all found to contain germanium. Topaz is abundant at the Morefield Mine. It occurs in large hemihedral crystals and in crystalline masses. Some of the crystalline masses weigh 200 pounds. Mr. Morefield reported one crystal 44 inches in length which weighed 500 pounds. The total amount of germanium becomes significant in masses of this size, even if the unit amount is small.

Of twelve samples of muscovite examined by Fitch, ten contained germanium. The shell-pink muscovite from the Rutherford Mine, however, is the only mica of this group which contains germanium. Spessartite from both mines contains germanium.

Lead appears in all of the feldspars and almost exclusively in the feldspars; the only other minerals in which it occurs are fluorite, mangano-tantalite, and shell-pink muscovite.

Table 2--Spectrum-analysis of rare elements in minerals from Amelia, Virginia[a]

Name of mineral	Mine[b]	B	Be	Cu	Ge	Pb	Sn	Zn	Rb	Li	K	Cs
Albite	R	..	..	..	..	Pb[d]	Sn	..	..	..	..	..
Beryl	R	..	Be	..	..	..	..	..	..	..	..	..
Beryl	M	..	Be	Cu[d]	..	..	..	..	..	..	..	..
Cassiterite	R	..	..	..	..	..	Sn	Zn[d]	..	..	..	..
Fluorite	M,R	..	Be	..	..	Pb	Sn	..	..	..	..	..
Mangano-tantalite	R	..	..	..	..	Pb	Sn	..	..	..	..	..
Mangano-tantalite	M	..	Be[d]	..	..	..	Sn	Zn[d]	..	..	..	..
Microcline	M	..	..	..	..	Pb	..	..	..	..	..	..
*Microcline	M,R	..	..	..	..	Pb	..	..	Rb	Li	K	..
Microlite	R	..	Be	..	..	..	Sn	..	..	..	..	..
Muscovite(amber)	M,R	B	..	..	..	..	..	Zn[t]	..	..	..	..
Muscovite (pink)	R	B	..	..	Ge	Pb	Sn	..	..	..	..	..
Muscovite(olive)	R	B	Be	..	..	..	Sn	..	..	..	..	..
Oligoclase (Ab)	R	B	..	..	..	Pb	Sn	..	..	..	..	..
Phenakite	M	B	Be	..	..	..	..	..	..	..	..	..
Sericite (pr)	R	B	..	..	..	..	Sn	..	..	..	..	..
Sericite (wg)	R	B	Be	..	..	..	Sn	..	..	..	..	..
Sericite (my)	R	B	Be	..	..	..	Sn	..	..	..	..	..
Sericite (cy)	R	B	..	..	..	..	Sn	..	..	..	..	..
Spessartite	R	..	..	..	Ge	..	Sn	..	..	..	..	..
Spessartite	M	..	..	Cu[d]	Ge	..	Sn	..	..	..	..	..
Topaz	M,R	..	Be	..	Ge	..	Sn	..	--	--	--	--
Tourmaline	R	B	Be	..	..	..	..	..	..	..	..	..
*Zinnwaldite	M	B[t]	Be	..	..	..	Sn	Zn[t]	Rb	Li	K	..

[a] t = trace; d = doubtful. [b] R = Rutherford Mine; M = Morefield Mine.

*Tests were made for rubidium, caesium, lithium, and potassium only after concentration.

Tin is the most widely distributed metal; it occurs in 17 out of 28 minerals. Tin is conspicuously present in the micas.

Zinc is doubtful in its occurrence.

Rubidium, once thought to be exceedingly rare, is now known to have wide distribution. Rubidium was present in the concentrates of green microcline and the zinnwaldite.

The lithium-content of the Amelia minerals is remarkably low. So far as has been observed it occurs only in the amazonstone, beryl, and zinnwaldite.

Zinnwaldite, an iron-lithia mica, in its form resembling biotite, occurs in considerable amount in the Morefield Mine. Recent chemical analysis has confirmed the spectroscopic determination. Caesium has been found definitely present although the amount has not yet been determined.

Whatever may be the significance, it is clear even from brief consideration that rare elements constitute an impressive and substantial proportion of the mineral constituents of these magmatic bodies.

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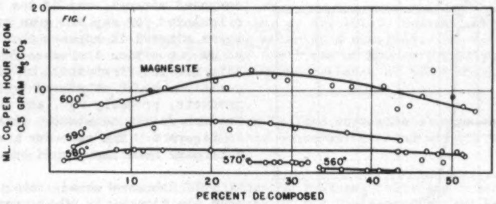
THE THERMAL DECOMPOSITION OF SOME CARBONATE MINERALS

Roger Clark Wells

Certain carbonates have long been known to decompose when heated, as shown by the ancient process of making lime from limestone and more recently in the manufacture of furnace-linings from dolomite and magnesite. Physical chemists have also studied the dissociation of such compounds with reference to the phase-rule, the heat of dissociation, the free energy of dissociation, etc., but most of the latter studies have been made with pure compounds prepared in the laboratory, with the result that many naturally occurring minerals have been studied very little if at all.

The experiments here described were made with carefully analyzed minerals for the purpose of explaining some discrepancies noted in the literature and in the behavior of certain carbonates, especially those of magnesium and iron.

The method used consisted in heating the mineral in a closed apparatus containing any desired gas and observing the resulting changes in the volume of gas, its pressure, and also the rate at which gas, chiefly carbon dioxide, was evolved or absorbed. It



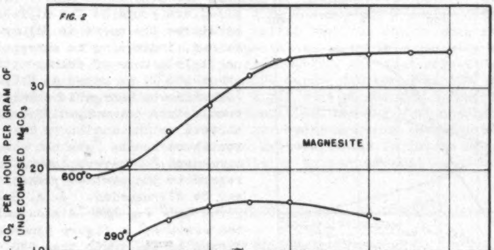


Fig. 1--Rate of evolution of CO_2 from magnesite in CO_2 at atmospheric pressure

Fig. 2--Rate of evolution of CO_2 from magnesite calculated per gram of undecomposed mineral would seem that at any given temperature the rate of evolution of gas from the powdered mineral should be directly proportional to the weight of mineral taken--this was found to be nearly the case, and the rate of evolution of gas was also found to be inversely proportional to the square of the gas pressure.

Magnesite

A very pure magnesite ($MgCO_3$) from Porterville, California, gave the results shown in Figure 1. The rate of evolution of CO_2 at different temperatures is here shown for a CO_2 gas-pressure of one atmosphere, and as actually observed with half-gram portions of powdered (80-mesh) magnesite. It may be seen that the rate is very slow below 560° C. From 580° to 600° the rate appears to increase slightly as the decomposition proceeds up to a certain point, after which it slowly decreases. However, this is for a continually decreasing quantity of undecomposed mineral, and if the rate is calculated for say one gram of undecomposed mineral it appears that the rate of decomposition increases fairly rapidly for the first third of the decomposition, as if catalyzed by one of the products, probably MgO, and thereafter becomes fairly constant. This is shown in Figure 2. The rate for a monomolecular reaction should be constant.

If the more steady rates observed when the mineral is 40 per cent decomposed are compared for different temperatures the curve in Figure 3 is obtained, indicating an extremely slow or negligible rate of decomposition at about 538°. As noted in Mellor's "Treatise on inorganic chemistry" the conclusions drawn by different observers on the action of heat on magnesian carbonate "are not always in agreement." Observations made without regard to the partial pressure of CO_2 may be disregarded. J. A. Hedwell gives 546° for the "dissociation-temperature," a figure apparently much closer to the truth than 680° found by H. le Chatelier. K. Friedrick and L. G. Smith observed a maximum thermal change in the heating curve at about 600° but this was probably the result of a balance of effects. Natural magnesite is stated by Grünberg (Zs. anorg. Chem., v. 80, p. 337, 1913) to begin its decomposition in CO_2 at 570 ± 15° and end it at 650 ± 20°. The corresponding figures in air are

FIG. 3

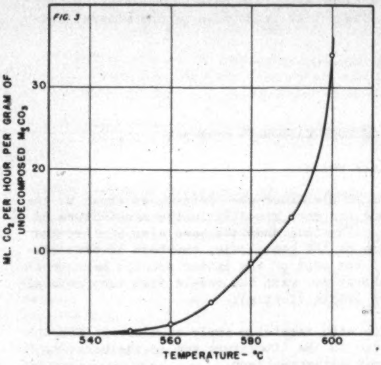


FIG. 4

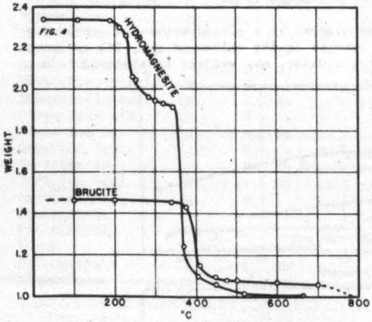


FIG. 5

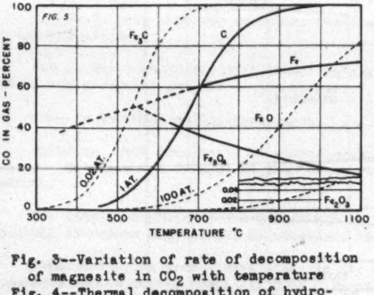


Fig. 3--Variation of rate of decomposition of magnesite in CO_2 with temperature

Fig. 4--Thermal decomposition of hydromagnesite and brucite in air

Fig. 5--Equilibria between iron oxides, carbon oxides, and carbon

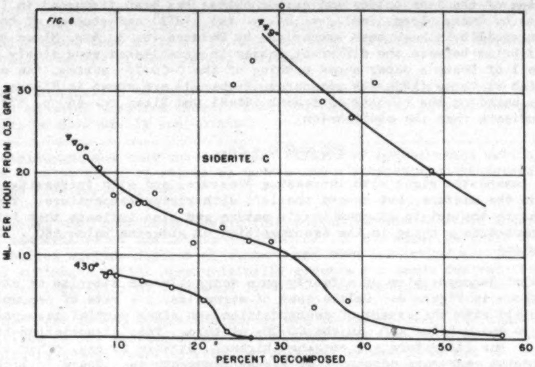


Fig. 6--Rate of decomposition of manganiferous siderite in CO and CO_2 at atmospheric pressure

360 ± 10° and 470 ± 15°. The writer would lower the first figure to about 545°.

Marc and Simek (Zs. anorg. Chem., v. 82, p. 49, 1913), however, find 402° for the "dissociation-temperature" of $MgCO_3$, using water as a catalyst. The writer believes that this figure is in error on account of their use of H_2O as a catalyst without considering possible errors from hydrolysis and the presence of other phases such as hydromagnesite ($Mg(OH)_2 \cdot 3MgCO_3 \cdot 3H_2O$).

The writer finds that the residue from ignited magnesite absorbs moisture much faster than it does carbon dioxide, and this hydrated material absorbs carbon dioxide faster than dry magnesium oxide does.

The curves for the thermal dissociation of hydromagnesite and brucite ($Mg(OH)_2$) in air have been determined by P. G. Nutting of the Geological Survey Laboratory, and are shown in Figure 4. These show marked differences, and are also different from that of magnesite, lending support to the belief that the conclusions of Marc and Simek are in error. The writer in some special tests on this question found that hydromagnesite heated 3 hours at 300° in dry CO_2-free air lost only 40 per cent of its water and 10 per cent of its CO_2. In dry CO_2 during 3.5 hours at 300° the loss was also 40 per cent of the moisture but only 4 per cent of the CO_2. Thus the removal of moisture from hydromagnesite under these conditions was far from complete. The curves in Figure 4 indicate that neither brucite nor hydromagnesite is completely reduced to MgO even in air at 400°. The formation of hydromagnesite in nature may be ascribed to the action of heat and moisture on magnesite or to the carbonation of brucite, as represented by the following equations

$$4MgCO_3 + 4H_2O \twoheadrightarrow 3MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O + CO_2$$

$$4Mg(OH)_2 + 3CO_2 \twoheadrightarrow 3MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O$$

Siderite

Siderite ($FeCO_3$) differs from magnesite in generally being less pure. Most siderites contain more or less magnesium or manganese carbonate, and results of their decomposition have accordingly varied with the sample used. Furthermore, siderite does not actually yield FeO on decomposing, as this oxide is so reactive that it decomposes CO_2, and H_2O if present, yielding magnetite and some CO or H_2. The two oxides of carbon thus produced may also react to yield carbon or iron carbides, thus forming a highly complex system not yet wholly understood.

The system of the iron oxides and carbon oxides has been discussed in its geologic aspects by Lasky (Econ. Geol., v. 26, p. 485, 1931) and studies of the iron oxide reduction equilibria have been summarized by Ralston (U. S. Bur. Mines Bull. 296, 1929). Equilibrium between the different phases is established very slowly below 600°. Figure 1 of Lasky's paper shows nothing of the C-CO-CO_2 system, the equilibrium lines for which at three different pressures (S-shaped) are shown in Figure 5. The heavy line is based on the results of Schenk (Stahl und Eisen, v. 46, p. 673, 1926). The curves indicate that the equilibrium

$$2CO \rightleftharpoons C + CO_2$$

is displaced toward the right with increasing pressure, and with increasing proportions of CO in the mixture, but toward the left with rising temperature. They offer suggestions as to the origin of graphite in nature and also indicate that FeO probably cannot be expected as a phase in the decomposition of siderite below 560°. Magnetite is formed instead.

The rate of decomposition of a fairly pure manganiferous siderite at atmospheric pressure in shown in Figure 6. Unlike that of magnesite, its rate of decomposition falls off rapidly with the extent of decomposition and after partial decomposition the action seems to cease below 430° in the CO-CO_2 mixture. The "dissociation-temperatures" given in the literature are somewhat higher. Strange to say, other siderites carrying magnesium carbonate decompose at higher temperatures. Space is lacking to describe further results here but they are expected to be published later in more detail in a Geological Survey report.

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GEYSER-BASINS AND IGNEOUS EMANATIONS

E. T. Allen

(Abstract)

The writer of this article endeavored to show:

(1) That the character of the magmatic emanations in the Yellowstone geyser-basins, and their function in hot-spring development, can be deduced from available evidence.

(2) That these emanations all have the magma in the gaseous state.

(3) That the water of these geyser-basins is largely (perhaps 85 to 90 per cent) of surface origin, and, because the supply is large, it descends to depths which a small supply could not attain without being wholly evaporated. At such depths the water dissolves and brings upward substances of low volatility, either magmatic sublimates or compounds formed at deep levels.

(4) That the rock of these basins is an important factor in the development of the alkaline springs, yielding all the silica in both waters and deposits and at least an important part of the sodium in the former. This follows from the work of Fenner.

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HYDROTHERMAL METAMORPHISM IN GEYSER-BASINS OF YELLOWSTONE PARK, AS SHOWN BY DEEP DRILLING

C. N. Fenner

The two drill-holes that the Geophysical Laboratory put down in the geyser-basins in Yellowstone Park in 1929 and 1930 gave information on a number of matters.

In the present article only the mineral changes that the rocks have undergone, and their significance, will be discussed. The results of this study fit in most satisfactorily with those that E. T. Allen obtained from his studies of the mineral content of the discharge-waters of the thermal springs.

The main conclusions to which the studies have led will first be given, and then the evidence on which they are based. With the conclusions in mind the bearing of the evidence will be more easily appreciated.

The conclusions are that the principal results of hydrothermal action in these rocks are a precipitation of silica as quartz and a substitution of potassium for sodium in the alumino-silicates.

The hole in the Upper Geyser-Basin (Old Faithful Basin) reached a depth of 406 feet. The temperature at the bottom was 180° C. In the upper part the drill passed through a shallow surface-deposit of sinter, and then penetrated a thick series of transformed sediments, which were originally gravels and sands derived from the mechanical disintegration of siliceous lavas. These continued to a depth of 220 feet.

From 220 feet to the bottom the boring was in lava-flows. The principal mineral transformations in the sediments and in the lavas have been of similar character. The secondary minerals that resulted from hydrothermal metamorphism are of fine grain. Close study by petrographic and analytical methods was required to identify them completely and to determine the significance of the changes of composition that the rocks had undergone.

The Upper Geyser-Basin is surrounded by rhyolites and dacites of great thickness, and no other rocks occur within a distance of many miles. As such rocks are made up chiefly of quartz and feldspar, the molar ratio of alkalis plus lime to alumina in them is nearly equal to unity. Some departure from unity in either direction may be expected because of the presence of a small amount of ferromagnesian minerals that carry lime and alumina in variable proportions.

If we take all the analyses of fresh rhyolites and dacites of Yellowstone made years ago by Gooch and Whitfield, we find that few show much departure of their molar ratios from unity. Fortunately, too, we have from the drill-hole itself a sample of unaltered rock. One of the drill-cores is a dacitic pitchstone that has almost completely escaped alteration. In this specimen the molar ratio of strong bases to alumina equals 0.992. It is probably fairly representative of the original composition of much of the material that the drill-hole passed through. In this specimen the analysis, on a volatile-free basis, shows 4.24 per cent Na_2O and 2.94 per cent K_2O. CaO equals 2.02 per cent and SiO_2 is a little less than 72 per cent. It may be considered a dacite of rhyolitic affinity.

The first step in alteration is shown by a specimen that came from a few feet above the last. The composition of this is almost identical with that of the other except for alkalis. Na_2O has dropped from 4.24 per cent to 3.62, and K_2O has risen from 2.75 per cent to 3.84. The increase of K_2O is the molar equivalent of the decrease of Na_2O. In the thin section this change is represented by a little secondary crystallization along perlitic cracks, whereas most of the glass is intact.

In most of the specimens, recrystallization of the groundmass is nearly complete, but the phenocrysts are almost unaltered. Several typical specimens of these thoroughly altered sediments and lavas were analyzed. The molar ratios found are 1.042, 1.027, 0.952, and 0.990. These ratios are probably as close to unity as we should expect them to have been in the original rocks, but in spite of the fact that the molar ratios have remained essentially unchanged, the relative amounts of K_2O and Na_2O are quite different. The respective figures are 8.72 per cent K_2O and 0.98 Na_2O, 9.68 K_2O and 1.52 Na_2O, 6.16 K_2O and 1.02 Na_2O, and 5.68 K_2O and 0.96 Na_2O.

Silica is high; in one it is more than 78 per cent, and in all of them the molar ratio of silica to other constituents is much higher than in the unaltered dacite. The comparative figures are 3.60 for the unaltered rock, and 5.92, 5.95, 5.43, and 5.68 for the altered specimens. In the thin sections of the altered rocks we find the high silica and high potash appropriately represented by a groundmass composed almost wholly of quartz and adularia.

From this evidence it is clear that the soda and silica, which form the principal mineral constituents found by Dr. Allen in the discharge waters of the thermal springs, could not have been derived by a simple leaching out of these constituents from the rocks. Removal of soda has been made up by its equivalent of potash, and though silica is brought to the surface in large quantity the amount in the rocks has actually increased. This evidence definitely excludes the possibility of simple leaching, but there may still be room for doubt whether the high silica and high potash found by analysis and shown by the minerals of the thin sections may not represent essentially the original composition. We might suppose, for instance, that the rocks varied considerably in the first place, and though dacites were present, most of them were rhyolites, and that there has been merely recrystallization without much change of composition. Under this supposition, the rising waters would have passed through the rocks without much gain or loss of mineral matter. That this does not represent the situation is shown by additional evidence.

Fresh lavas of such high content of silica and potash and low soda and lime as are shown by these rocks are not unknown, though they are rather unusual, but in such rocks we expect to find that the phenocrysts are quartz and orthoclase. Ferromagnesian minerals should be deficient. In these altered lavas the original phenocrysts remain as witnesses of the original composition, and we find them to be soda-lime feldspars of oligoclase-andesine composition, and a considerable amount of pyroxene and iron ore. The phenocrysts are, in fact, practically identical with the phenocrysts of the unaltered dacitic pitchstone that has been described. They are incompatible with the present groundmass.

Furthermore, there is a certain peculiarity of the pyroxene phenocrysts of the fresh dacite that appears also in many of the altered rocks. These pyroxenes are of two varieties, the ordinary biaxial crystals and the rather rare uniaxial variety that is called pigeonite. This identity of characteristics of phenocrysts points to a close similarity of original composition of the altered lavas and the specimen of dacitic pitchstone. We believe, therefore, that the alteration has been not merely a recrystallization of a glassy or finely felsitic groundmass of a high-potash high-silica rhyolite, but implies addition of silica and substitution of potash for soda. This applies especially to the lavas found in the lower part of the drill-hole. The sediments of the upper part were of somewhat more rhyolitic composition originally, but probably not of the rather extreme character they now show.

Dr. Allen has found that the waters discharged from the hot springs carry relatively large amounts of silica and soda. Other bases than soda and a little potash are practically absent, but chloride and bicarbonate radicals are present. When his data are correlated with those derived from a study of the rocks, the conclusion is plain that waters rising from greater depths than were penetrated by the drill-hole bring with them silica and the chloride and bicarbonate of potassium in solution. As they pass through the rocks, part of the silica is deposited and most of the potassium is abstracted by substitution for sodium in the aluminosilicates. The sodium driven out and the excess silica are carried upward. Close to the surface the waters become so depleted in potassium that substitution nearly ceases. Sodium aluminosilicate is recrystallized in hydrated form as the zeolites analcite and clinoptilolite. By subsidiary reactions a little calcite, chlorite, and goethite are formed.

It seems clear, therefore, that the original source of the silica and potash that have been added and that play such a prominent part in the metamorphism must be sought in deeper regions than were reached by the bore-hole. Enormous quantities of silica and potash have been transferred from some lower source to these higher levels.

The alteration that these rocks have undergone is different in some respects from anything commonly recognized, but it is doubtful if it is actually exceptional in any manner. If rocks that had been altered in the same way were found in a region where the obvious surface-evidences of hot-spring action had been removed by erosion, most of them would probably be regarded as fairly normal rhyolites or dacites. The texture and general appearance are not so different as to be impressive on casual examination. Possibly it would only be after intensive study, supplemented by analyses, that the incongruity of phenocrysts and groundmass would be recognized. Usually an intensive study of such ordinary-looking rocks is not called for. There may be many occurrences of similar hydrothermally metamorphosed rocks in volcanic regions, which, in absence of complete data, have been looked upon as normal lavas. Even analyses may have been accepted as representing original compositions.

So far, not much has been said about the drill-hole in Norris Basin. This hole reached a depth of 265 feet, and the temperature at the bottom was 205° C. At the surface and for a small depth the rock shows the effects of leaching by acid sulphate waters. Feldspar phenocrysts have been dissolved out, leaving cavities of characteristic form. Analysis of this rock shows little of the original material to be left but silica and alumina. This leaching rapidly diminishes with depth and at 30 to 35 feet hardly a trace of the effect is visible. The acidity to which it is due is plainly a surface-condition, brought about by the oxidation of H_2S.

From 35 feet to the bottom of the hole the cores show the operation of processes similar to those described for the Upper Basin, but the evidence is not so clearly demonstrable. In many of the specimens it is easy to see that changes have taken place, but without the evidence obtained from the Upper Basin their significance might not have been recognized. The reason is that the rocks here were of more rhyolitic composition in the first place, as shown by their phenocrysts of quartz and orthoclase, and substitution of potassium for sodium has not been so complete.

In some of the core-specimens small vugs carry recognizable crystals of quartz, tridymite, and adularia. These three minerals, with a little pyrite, make up a large part of the fine-grained groundmass and represent almost wholly the results of hydrothermal action in the rocks.

Although these minerals are plainly secondary, they (except pyrite) might be regarded as merely a recrystallization of the original groundmass. They are not obviously incompatible with the phenocrysts. Chemical analysis does not show results that might not be interpreted in the same way, for there is not the great excess of potash over soda that the cores from the Upper Basin show. The results in four analyses were 4.94 per cent K_2O and 2.56 Na_2O, 4.91 per cent K_2O and 2.85 Na_2O, 5.50 per cent K_2O and 2.98 Na_2O, and 5.12 per cent K_2O and 2.90 Na_2O. Molar ratios of strong bases to alumina are close to unity. Dr. Allen's work, however, shows that the discharge-waters of the hot springs in Norris Basin also carry a large excess of soda and silica, and when we recall the significance that these had in the Upper Basin, it seems reasonable to suppose that the same processes are at work here, but that they have not gone on for so long a time. Nevertheless, there is reason to suppose that their action has extended over a period of thousands of years.

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VOLCANIC DUST IN RELATION TO CLIMATE

W. J. Humphreys

In May 1784 Benjamin Franklin wrote a most interesting account of the "dry fog" that during the previous summer, 1783, persistently covered Europe and North America, and which rain, nor wind, nor sunshine could dispel. It so weakened the rays from the Sun that "when collected in the focus of a burning glass they would scarce kindle brown paper." He surmised that this fog might be "the vast quantity of smoke, long continuing to issue during the summer from Hecla, in Iceland, and that other volcano which arose out of the sea near the Island, which smoke might be spread by various winds over the northern part of the world."

Franklin further surmised that the exceptional severity of the winter of 1783-84 might have been owing to this persistent dry fog, and suggested a study of the records of other such occasions with the view to applying the knowledge thus obtained to seasonal forecasting whenever, in the future, such a fog might appear.

This fog was, we may be sure, of volcanic origin, from Skaptar Jökull in Iceland

and, especially, Asama in Japan. However, Franklin's logical conjecture that abnormally cold seasons would follow the occurrence of such persistent dry fogs seems soon to have been forgotten. Nor was any similar idea, so far as I know, advanced by any one else for well over 100 years, not indeed until 1901, when the cousins, P. and F. Sarasin, published a paper in which they proposed the theory that the glaciation of the ice-ages might have been caused by the absorption of solar radiation by veils of volcanic dust in the higher atmosphere.

Nor did this paper attract much attention either, perhaps because it seemed to claim too much. Furthermore, there was in it a decided uncertainty, for clearly the dust-veil must, to some extent, absorb the outgoing Earth radiation as well as the incoming solar radiation, and the net result on the temperature of the Earth obviously depends on which of the two streams of radiation the dust most completely absorbs. If the two absorptions were equal the temperature of the Earth would not be affected by the dust. If the absorption of the Earth radiation is the greater of the two then the temperature of the Earth actually will be increased by the dust. If, finally, the absorption of the solar radiation is greater than that of the Earth radiation then the temperature of the Earth necessarily will be decreased by the dust-veil.

All this is based on the assumption that the action of the dust is only that of an absorber and an emitter of radiation. We know now, however, that as a reflector and as a scatterer of radiation it probably is far more effective than it is as an absorber, and we also now have the necessary data for a logical approximate solution of the problem, and the observational records with which to test our solution.

From temperature-records that run back to about 1750 it appears that for, roughly, one to three years after every volcanic explosion that put large amounts of dust far above the highest clouds the average temperature of the hemisphere in which the explosion occurred, and in some cases of the entire Earth, was 1° C or thereabouts, below normal. Also, from pyrheliometric measurements that have been continuous since just before the eruption of Krakatoa in August, 1883, we know that these dust-veils do decrease the intensity of the incoming solar radiation, from a few to even 20 per cent. Furthermore, these measurements and sky-observations show that it takes many months to two or three years for the finer dust to settle out of the upper cloudless atmosphere. Then, too, from the halo this dust forms about the Sun we know that the average diameter of these dust-particles is about 1.85 microns. And of course we know, in general, the composition of the rocky material of which they consist.

From this information sound calculations of at least the order of magnitudes can be made.

Thus, according to theory, it would take from one to three years for such dust to settle from say the 40-km level down to that of the highest clouds, just as observation shows to be the case. Again, theory indicates that the cloud-veil must shut out solar radiation far more effectively than it shuts in Earth radiation, and therefore must lead to a decrease of the average temperature. This, too, agrees with observation and record.

Theory further shows that it does not require a very large amount of dust in the upper air to produce important insolational and thermal effects at the surface of the Earth. Indeed a little calculation shows that if a cubic kilometer of rock were divided into 175 equal portions, so little as just one of these, if reduced to spherical grains having the diameter of volcanic dust-particles, and evenly distributed through the upper air, would reduce the intensity of the sunshine by about one-fifth. And as this dust presumably is flaky rather than spherical probably the 350th part of a cubic kilometer of rock would suffice.

From this in turn it is evident that even enough volcanic dust in the atmosphere to bring on an ice-age would not necessarily leave any certain trace of itself on the face of the Earth. Surely the amount of dust that would reduce the intensity of the sunshine by 20 per cent, if long continued, would suffice tremendously to extend our fields of ice and snow, but that amount, the 350th part of a cubic kilometer of rock, even once a year for 100,000 years (a needlessly long period) would make, if evenly spread over the Earth, a layer only one-half a millimeter thick. Clearly then, it would be utterly useless to hunt for any evidence, in the form of dust-layers, that volcanic activity might have affected the climates of the past. And yet we are certain that throughout the geologic ages, as now, every volcanic explosion that filled the upper air with dust more or less decreased the temperature of the Earth and correspondingly modified its climates. Indeed merely one Krakatoa a year, and there may have been centuries together when there were more than that, certainly would profoundly modify--would appreciably chill--the climates of all the world.

One more point. To establish in this way a long period of cooler climates would not, absolutely not, require an equally long and continuous volcanic activity. Because soon the range of ice and snow would be extended, and by virtue of their greater power than that of bare soil to reflect sunlight the solar heat virtually would be decreased. After a time, in this accumulative way, the ice and snow would cover so great an area as to more or less maintain themselves, whatever the state of the skies, dusty or clean.

It is not urged here that the glaciation of the ice-ages was owing to the presence of volcanic dust in the upper atmosphere, but it is insisted that volcanic dust is, and always must have been, a factor, probably at times an important factor, in climatic control--a factor that always brings about lower temperatures. And since this dust is spread more or less evenly by the winds of the stratosphere over the whole face of the Earth it is a factor of world-wide interest, and must be given universal attention and study. That is the reason for this paper, a plea that a well-known, though perhaps not fully appreciated, world problem be given the attention it so fully deserves.

U. S. Weather Bureau,
Washington, D. C.

THE RÔLE OF VOLATILES IN THE FORMATION OF VIRGINIA TITANIUM DEPOSITS

Clarence S. Ross

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(Abstract)

The feldspathic rock with which the titanium deposits of Virginia are associated appears to be an anorthosite, although the plagioclase is somewhat more sodic than in normal anorthosites. That is, this rock shows evidence of having been introduced as a mush-like mass of crystals and interstitial magma, and of undergoing very thorough crushing during introduction. This rock was later very thoroughly altered by hydrothermal solutions which migrated through the fractures in the feldspar rock and new minerals including the titanium minerals--rutile and ilmenite--were introduced. The elements introduced into the feldspathic rock were TiO_2, FeO, MgO, P_2O_5, and F. The other elements that went into the formation of new minerals were derived from the feldspar originally present. There was a distinct order in the abstraction of the introduced elements from the carrying solutions, as shown by the zonal relations of the secondary minerals. Ferrous iron was abstracted first in the formation of the ferromagnesian silicates and ilmenite. Magnesium and titanium, in the absence of iron, traveled farther from the source of the solutions and deposited rutile and magnesian silicates. At greater distances most of the introduced elements had been abstracted from the solutions but notwithstanding this the feldspar was extensively altered, but without any marked changes between the chemical composition of the original feldspar rock and the resulting altered rock.

The mineralizing elements--TiO_2, FeO, MgO, P_2O_5, and F--appear to have been derived from some deep-seated, highly ferromagnesian rock that is probably genetically related to the feldspar rock. The method of segregation of these materials from this rock is a highly speculative problem, but it seems probable that P_2O_5 was distilled off (the second boiling point) in a late stage in the cooling and crystallization of this rock. This, together with a little F, combined with calcium previously present in the plagioclase to form apatite. It also seems possible that under the high pressure of deep-seated formation titanium may also have been distilled off as titanium tetrafluoride in the same manner.

U. S. Geological Survey,
Washington, D. C.

VOLCANIC ACTIVITY IN 1933

E. G. Zies

The first accounts of activity in volcanic areas are usually obtained from consular and newspaper reports and are only then recorded if the disturbance caused by an explosion, a fall of ash, flow of lava, or steam-cloud is more than purely local in its manifestations. The news value of such events is greatly enhanced if the eruption is accompanied by loss of life or destruction of property. This point is illustrated by the accounts in the newspapers of the eruption of Vesuvius which began in March and continued until June 1933. A lurid picture was drawn of the destruction of life and property, Naples was doomed, etc., etc. The reports of the activity were so greatly exaggerated and so needlessly alarmed the population that the Observatory at Vesuvius was asked to discontinue its bulletins. The newsmen finally contented themselves with the statement that the activity was now of interest only to the scientists. This statement came closer to the truth than the reporters probably realized for it is becoming more and more apparent that the periods preceding and following an eruption are from a scientific viewpoint as important as the period of eruption itself; as a matter of fact, they are especially important in establishing the empirical background that will be required before we can hope to forecast an eruption. This report for 1933 includes not only the volcanic disturbances of far-reaching influence but also those whose effect was confined to the vent itself.

Chile was in 1933, as in 1932, the scene of intense volcanic manifestations. In 1932 the activity was confined to a group of volcanoes centering on Quizapú situated in the Andes about 300 kilometers to the south of Santiago. In 1933 a group of volcanic centers about 300 kilometers further south quite suddenly erupted; the Quizapú group remained more or less active during the greater part of 1933. The active vents were Llaima, Lonquimay, and Villarica. The paroxysmal stage continued throughout the first week in January (1933) and was most intense at Llaima. Severe electrical storms and flames accompanied the outbreak. The ash-cloud was maintained for several days at a height of ten kilometers above the crater. The ash covered an area hundreds of square miles in extent and destroyed much of the vegetation. The air-temperatures in the towns nearby rose rapidly and became intolerable. It is reported that lava was extruded from the vents, but this statement awaits confirmation; the name lava is often given to the old clastic material thrown out during the violent explosion of a volcano that has been inactive over a long period. Seismic disturbances and the characteristic Earth rumblings preceded the outburst and continued during the explosive stage. The volume of ash ejected by Lonquimay reached such proportions that the snow- and ice-cap that had accumulated over a long period of years gradually melted away.

Calbuco, another member of the same group of volcanoes, became active about the same time. The spectacular eruption of ash was accompanied by intense seismic disturbances.

The volcanoes Quizapú and Descabezado located in the northern group have remained more or less active since April 1932. In January, Descabezado emitted huge amounts of ash which rapidly melted away the snow-cap and flooded the streams. The rapid disappearance of the snow had serious consequences during the year inasmuch as the nearby towns depended on it for their water-supply.

The volcano Lascar near San Pedro exhibited renewed activity in October.

The reports indicate that the Chilean volcanoes continued active through the greater part of the year. It is doubtful if detailed accounts will be forthcoming until sufficient time has elapsed for the various observers who visited the two volcanic areas to complete their studies. It is the opinion of Hans Reck (Zs. Vulkanologie, v. 15, p. 194, 1933) that the extensive activity in the northern group of Chilean volcanoes (centering on Quizapú) is not to be referred to individual and isolated hearths but to a common deep-seated source. The same argument applies to the southern group centering on Llaima; as a matter of fact, it is probable that both groups have a common source.

Vesuvius--Renewed activity was observed at Vesuvius in February. Professor

Malladra forecast the spring activity and based his prediction partly on the case history of the volcano and partly on the swarm of Earth tremors that occurred during the first two days of February. The volcano became quite active on the third day and remained in the Strombolian condition until May 22, when lava began to issue from the central cone. June 2, the lava flowed more freely, poured over the crater rim into the Valley dell' Inferno and covered the lava of 1927-30. The explosive phase lessened after the lava appeared and came to a close late in June.

San Martin situated in the state of Vera Cruz, Mexico, after an apparently quiet period of over a hundred years became explosively active on May 14. The Government sent investigators to the volcano, but as yet no reports of their findings have been received.

The Bulletin of the Netherlands East Indian Volcanological Survey describes the activity of the volcanic areas in the East Indies. No spectacular outbursts were reported but it is of considerable interest to volcanologists that this Survey has been able to continue its work in spite of bad economic conditions. The extensive volcanic area in Java that embraces such active vents as Anak Krakatau and Merapi (Middle Java) has been studied throughout the year. The new cone Anak Krakatau that rose out of the sea several years ago attained a height in 1933 of approximately 89 meters above sea-level. It was very active during the first six months of the year; the explosions so characteristic of Anak Krakatau were particularly pronounced during this period; on many days they came only a few minutes apart and the accompanying column of steam, water, and ash rose to heights of 1000 meters or more. The reviewer wishes to call attention to the excellent photographs by Dr. Stehn (N. E. I. V. Survey Bull. No. 63); the picture of the electrical disturbance in the eruption cloud is unusually good.

Merapi in Middle Java is probably one of the most continuously active volcanoes in the world and in view of its proximity to a densely populated area is a potential source of great danger. The Director of the Netherlands East Indian Geological Survey and the members of the staff of the Volcanological Survey deserve great credit for continuing their important observations at this center; the work, as the writer knows from experience, is greatly hampered by many obstacles. The active lava-dome is reached only after an arduous climb over loosely piled lava-blocks; the suffocating character and high temperatures of the gases escaping from the fumaroles in the recesses on the lava-dome are particularly annoying and can be dangerous. Both the safety of the population and the progress of volcanology make it desirable that the observations at Merapi be continued and extended. These observations are required in building up the case-history of a volcano; this must be done if accurate predictions of increased activity are desired.

The very high temperatures of the emanations (maximum over 600°) persisted at several vents throughout the greater part of the year. The chemical activity of the gases is probably a matter of some importance in providing paths of egress for the gases escaping from the lava in the conduits. A series of eruptions accompanied by glowing clouds is recorded for the early part of October. Fortunately, no serious damage to property occurred and no lives were lost. Dr. Stehn and his associates took advantage of the excellent opportunity for making observations. Attention should also be directed to the publication of No. 12 of the well-known series "Vulkanologische en Seismologische Mededeelingen." It contains two excellent papers, one by Dr. M. Neumann van Padang on "De uitbarsting van den Merapi (Midden Java) in de jaren 1930-1931" and the other by Dr. M. Hartmann on "Bijdrage tot de kennis van gassen, sublimatie- en inkrustatieprodukten, en thermale wateren in de Merapiladoe's" (summary in English).

Central America--Izalco has been almost continuously active for the past five years. Explosive eruptions occur at intervals of half an hour; they are accompanied by steam, dust, and clastic material; in addition about twice a year lava issues either from the crater or from the flank of the volcano. Two lava-eruptions were reported for 1933, one on July 25 and one on November 30. The latter was one of the most violent eruptions in years. Considerable damage was done to nearby coffee plantations and to livestock. Izalco has probably furnished more lava-flows since its birth in the eighteenth century than any other Central American volcano; it must be reckoned among the most active volcanoes of the world.

Momotombo in Nicaragua has been in the solfatara stage for several years. A relatively mild eruption was reported in October.

Santa Maria in Guatemala has not staged any spectacular eruption during 1933, but there has been active emission of steam from the hundreds of fumaroles on the lava-dome. Avalanching of rock has persisted throughout the year.

The activity at Mt. Pelée on the island of Martinique has persisted throughout 1933 in a somewhat abated form. It is a matter of considerable interest to volcanologists that F. A. Perret has been able to continue in 1933 his observations at the Volcano. He has had an excellent opportunity to study the activity of Pelée, especially the glowing clouds. Those who are familiar with his report on Vesuvius are eagerly looking forward to the written account of his labors.

A violent eruption was reported on one of the volcanic islands in the Ryukyu archipelago, Japan. No details of the manifestation are as yet available.

The last scene of volcanic activity for the year was located in the crater of Mauna Loa on the island of Hawaii. Dr. T. A. Jaggar reports that on November 1 and 2, 1933, he observed blue fumes and puffing vapor in the main crater of Mokuaweoweo. The blue fume is usually an indication of relatively high temperatures, 300° or more. It is his belief that this gaseous phase heralded the big eruption which took place on December 2. On this date the floor of the summit crater, Mokuaweoweo, was split along the upper end. Lava poured out and flooded a portion of the crater-floor. The outpour of lava was accompanied by fountaining and active fuming which continued until December 18. The seismic disturbances covering the period from November 28 to December 31 were recorded and the reader is referred to Dr. Jaggar's detailed account in The Volcano Letter. Dr. Jaggar also reports that Kilauea remained inactive throughout the Mauna Loa disturbance.

Sources of information: Bulletin of the Netherlands East Indian Volcanological Survey, Bandoeng, Java; The Volcano Letter of the Hawaiian Volcano Observatory; Zeitschrift für Vulkanologie; private communications; and consular and newspaper reports.

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THE VISCOSITY OF MAGMAS

GENERAL CONSIDERATIONS CONCERNING THE VISCOSITY OF LIQUIDS

R. E. Gibson

(Abstract)

This paper, given as an informal introduction to the symposium on the viscosity of magmas, contained a brief review of the study of the viscosity of liquids in general. Starting from the formal definition of the coefficient of viscosity the author outlined the various methods used in the measurement of this quantity, including the observation of uniform flow through capillary tubes, the rotating cylinder method, the terminal velocity of falling rigid spheres or rising bubbles in liquids, the rate of elongation of a rod, and the rate of sag of a rod supported horizontally at two points. In the last two methods coefficients of viscous traction are measured and the relation of this quantity to the coefficient of viscosity is well discussed by Trouton (Proc. Roy. Soc., v. 77, p. 926, 1906). These last two methods which are especially suitable for the measurement of the coefficients of viscosity of highly viscous liquids (for example, pitch at room-temperature) are of especial significance in geophysical problems. The well-known formulae connecting the rate of laminar flow of a liquid, the rate of sinking of a solid mass in a liquid medium, or the rate of rise of a gas-bubble in a liquid all involve powers greater than unity of the dimensions of the masses under consideration. Simple calculations show that in masses of dimensions of the order of those met in geological problems important movements of matter may

occur in liquids whose viscosity is 10^9 c.g.s. units or even greater.

A survey was also made of the theories which have been proposed to account for the viscosity of liquids. Andrade (Phil. Mag., v. 17, pp. 511 and 698, 1934) has recently formulated a theory of viscosity which gives very satisfactorily the viscosity of elements near their freezing-points, but which for lack of data cannot be applied to compounds and certainly not to silicate magmas. In the same way the expression for the temperature-coefficient of viscosity which Andrade has applied with excellent results to about one hundred liquids cannot be applied to silicates, as one of the necessary data, namely, the coefficient of thermal expansion, is known in only a few scattered instances.

As, furthermore, the effect of one substance on the viscosity of another is considerable but up to the present entirely unpredictable, it is concluded that at present very little light on the viscosity of complex mixtures may be thrown from theoretical considerations and that direct measurements under different conditions of pressure and temperature offer the most promising mode of attack of the problems of the viscosities of magmas.

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VISCOSITY DATA FOR SILICATE MELTS

N. L. Bowen

Introduction

For a number of reasons a knowledge of the viscosity of igneous magmas is of much importance to the petrologist. In the passage of magma through channels in the Earth, in its pouring out as lava upon the surface, in the sinking of crystals and the rise of gases, and in many other processes in which magma participates viscosity is a dominant controlling factor. Obviously little can be done in the way of direct measurement of the viscosity of magmas while these actions are in progress. Estimates have been made of the viscosity of a lava-flow in Hawaii from the rate of its flow down a slope (G. F. Becker, Am. J. Sci., v. 3, p. 29, 1897; his estimate--60 times the viscosity of water--is only about 1/200th of the viscosity of a basaltic melt measured in the laboratory by Kani), and the play of lava-fountains there and elsewhere has afforded a general idea of the magnitude of the viscosity of basic lavas. At the other extreme, visual demonstration of the enormous viscosity of salic lavas, under the observed conditions, is available in the slow rise of volcanic spines. In spite of the fact that these observations of natural phenomena get closer to the heart of the problem, actual measurement of silicate viscosities can be made only in the laboratory. Few of these measurements have been made with geologic problems in mind. For the most part the investigations have been undertaken because a knowledge of the viscosity of silicate melts is of great practical importance in certain industries. Such knowledge is fundamental to intelligent control of slags by the metallurgist. The glassmaker is even more emphatically at the mercy of viscosity, for his product must have that property in appropriate adjustment with other properties, not only at the high temperatures at which glass is melted and "fined," but also at the intermediate temperatures at which it is worked into shapes, and again at the low temperatures at which it is annealed. For these reasons metallurgists have measured the viscosity of slags at temperatures at which they are comparatively thin liquids, and glass technologists have examined glasses throughout the range of temperatures in which they pass from thin liquids to thick liquids and eventually to material which, in the mechanical sense, is a rigid solid. Such of these measurements as have more direct bearing upon geologic problems may now be reviewed, together with those measurements that have been undertaken with geologic considerations primarily in view. For this purpose it is convenient to group slags and "basic" melts together, while glasses and salic melts may be treated as another group.

Slags and "basic" melts

A number of studies have been made of the viscosities of slags, especially of iron blast-furnace slags and of mixtures related to them in composition. Thus Feild studied actual slags (A. L. Feild, Am. Inst. Mining Eng. Bull., No. 122, pp. 307-332, 1917) and, together with Royster, mixtures of the system, $CaO-Al_2O_3-SiO_2$, which is of fundamental significance in connection with slags (A. L. Feild and P. H. Royster, U. S. Bur. Mines Tech. Paper No. 189, 1918). In the latter investigation the conclusion was reached that there were maxima and minima on the viscosity-curves that were definitely related to the fields of stability of crystalline compounds. Maxima were said to occur at quintuple points and minima at binary eutectics. This conclusion is altogether at variance with the observed facts in other silicate systems and with the general impression one gains (without actual measurements) in handling liquids of the system, $CaO-Al_2O_3-SiO_2$. It is not surprising, therefore, that later work has failed to confirm the results of Feild and Royster. Thus Herty and associates, as the result of a study of viscosity-relations in the system, $CaO-SiO_2$, reached the conclusion that "the presence of eutectics has no effect on viscosity" (Herty, Hartgen, Heidish, Metcalfe, Norris, and Royer, Cooperative Bulletin 47, U. S. Bur. Mines, Carnegie Inst. Tech., and Mining and Metallurgical Advisory Board 1930, p. 20). But Herty does believe that he found a minimum at the composition of a compound ($CaSiO_3$), whereas the results of the very elaborate investigation of the four-component system, $CaO-MgO-Al_2O_3-SiO_2$, point to the conclusion that, while there may be maxima or minima of viscosity, these have no relation to compounds, eutectics, or any of the maxima or minima on the crystallization-surface (McCaffery, Lorig, Goff, Oesterle, and Fritsche, A. I. M. M. E., Tech. Publ., No. 383, 1931). The conclusion agrees with the observations on the viscosities in other silicate systems studied by glass technologists and likewise with the general impression one gains in working with silicates. No simple relation of viscosity to crystallization-temperatures is therefore to be expected nor is there any hope of prediction of viscosities for complex mixtures on the basis of any such considerations. Reliable results come only from elaborate series of careful measurements.

In spite of disagreement upon details of this character the results obtained by different observers upon mixtures of interest to petrologists are in reasonably good agreement. Among these may be mentioned the measurements of Feild and of McCaffery et al. on diopside, their results at 1450° being respectively 7.8 and 3.8 poises. (The results of Doelter on diopside are altogether inexplicable.) For the composition $CaSiO_3$ at 1600° Herty et al. found a viscosity of 4 poises and McCaffery et al. 2.4 poises. Before any of these results were available Bowen (N. L. Bowen, Am. J. Sci., v. 39, p. 185, 1915) had made an estimate of the viscosity of the molten mixture, $CaSiO_3$ 30 o/o $MgSiO_3$ 70 o/o, at 1450°, from the rate of sinking of olivine crystals in it and suggested the value 4 poises. It appears, therefore, that even this rough method is adequate to give a value of the viscosity of the correct order of magnitude. Melts of a pyroxenic character are, then, of decidedly low viscosity.

In working with feldspathic melts, even of the most basic feldspar, anorthite, one realizes that they are distinctly more viscous. The measurements of McCaffery and associates bear this out. They find for anorthite 25 poises at 1600° and 60.5 poises at 1500°. Other feldspar liquids have higher viscosities. There are no data for intermediate plagioclases but on a later page some results for albite are given.

The measurements upon these mineral types lead us naturally to measurements upon basalt which is largely a mixture of pyroxenic and feldspathic material. Recently Kani has made direct determinations of the viscosities of three basalts and a nepheline basalt remelted in the laboratory (K. Kani, Proc. Imp. Acad. Tokio, v. 10, pp. 29-32 and 79-82, 1934). Full details of his method are lacking, so that it is not possible to say whether precautions were taken against a change of state of oxidation of iron. Apparently the pressure was the ordinary atmospheric pressure and certain substances were volatilized from the molten rock-substance during the experiments. His results are given in Table 1. It will be noted that at any given temperature there was little difference between the two olivine basalts and the andesitic basalt, but the much less siliceous nepheline basalt gave a considerably lower value. These basaltic melts have low viscosities at their melting temperatures and therefore do not undercool readily. On the contrary, when the temperature is lowered below a certain value for each rock, crystallization takes place freely, as Kani observed, and the apparent viscosity increases enormously as a result of the fact that the material has now become a mush (see values in Table 1).

Table 1--Compositions and viscosities of remelted basalts, after Kani

Compound	Olivine-basalt, Gembudô	Olivine-basalt, Kônoura	Andesitic basalt, Motomura	Nepheline-basalt, Nagahama
	o/o	o/o	o/o	o/o
SiO_2	49.29	49.24	51.80	35.66
Al_2O_3	18.49	16.81	15.00	11.97
Fe_2O_3	2.38	6.16	3.68	5.19
FeO	6.77	3.60	10.14	9.69
MgO	6.09	8.02	5.36	8.35
CaO	8.14	9.49	9.77	14.39
Na_2O	3.93	2.67	1.76	3.65
K_2O	1.79	1.09	0.32	1.89
H_2O	0.88	1.50	0.62	4.04
TiO_2	2.22	1.33	0.60	3.74
P_2O_5	Tr.	0.43	0.31	1.37
MnO	0.22	0.17	0.20	0.30
Totals	100.20	100.51	100.56	100.24
Temp.	**Viscosity**	**Viscosity**	**Viscosity**	**Viscosity**
°C	poises	poises	poises	poises
1400	136.68	119.73	138.55	70.76
1350	175.83	136.37	182.94	88.11
1300	296.15	172.67	259.12	97.34
1250	656.15	336.59	541.51	117.14
1200	3180.60	731.82	31168.00	190.00
1150	37897.00	Rapid increase	79470.00	Rapid increase

Kani's observations regarding the onset of crystallization are in entire accord with those of all individuals who have investigated basic silicate melts. Some petrologists, considering the matter in a theoretical manner or from the point of view of supposed analogies, have advocated the view that large bodies of basic magma might persist in the Earth for long periods in an undercooled condition but it is doubtful if anyone with experience of silicate melts would subscribe to such an opinion. There are, of course, substances of an intermediate character in this respect, indeed anorthite, already mentioned, is one of them. In small mass in the laboratory it is possible to undercool anorthite and to study the viscosity at temperatures below its equilibrium crystallization-temperature, but it is doubtful if this could be accomplished with any large body of it in nature, were there any such.

Still other substances undercool with great readiness to the condition of a glass and we shall now pass to a consideration of them.

Glasses and salic melts

Our knowledge of viscosities of liquids of high silica-content comes largely from measurements made on commercial glasses. Ordinary glass is a lime-soda silicate, a composition with little relation to any natural magma, so that the results obtained with it have only a general orienting value for the petrologist. Fortunately, however, glasses are ordinarily melted in clay-containers, which they attack and thus acquire alumina, a step in the direction of natural magmas. The glass technologist has found it desirable to investigate the effect of alumina upon the viscosity of glass.

Table 2--Compositions of three glasses studied by English

No.	SiO_2	Na_2O	Al_2O_3	CaO	Fe_2O_3
1	74.05	25.34	0.24	0.21	0.14
2	72.05	20.62	6.85	0.20	
3	71.56	15.28	12.69	0.31	

The fundamental research is by S. English who, starting with a certain sodium silicate glass, determined the effect of substituting alumina for some of the soda (S. English,

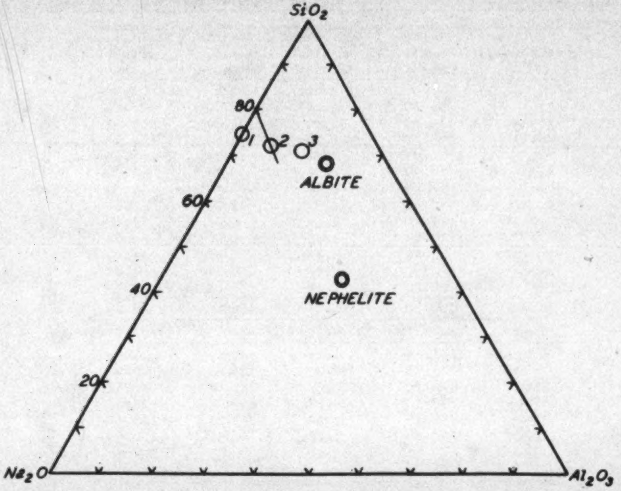

Fig. 1--Showing compositions of three glasses of Table 2 and their relation to albite (The line passing through point 2 is an approximate isokom)

J. Soc. Glass Tech., v. 8, pp. 205-251, 1924). The composition of his series of three glasses is given in Table 2. These three glasses are plotted in the triangular diagram, Na_2O-Al_2O_3-SiO_2 (Fig. 1), the point for each being numbered in accordance with the numbers assigned to the glasses in Table 2. Examination of Figure 1 shows that the points indicating these glasses lie nearly on a straight line which passes close to the composition of albite, an important constituent of many salic rocks. It would seem possible to obtain by extrapolation from the results of English upon his aluminous glasses between 500° and 1400° a close estimate of the viscosity of albite-glass at such temperatures. The results of the viscosity-measurements of English for his three glasses are plotted in Figure 2. It would be expected from the composition relations brought out in Figure 1 that the viscosities of albite-glass would be closely represented by another parallel curve approximately equally spaced above his three curves. Actual determinations were made of the viscosity of albite-glass to ascertain whether this is true, but it was found that at any temperature the viscosity of albite-glass is enormously greater (of a totally different order of magnitude) than that indicated by this extrapolation. These measurements were made by a comparison method which, as carried out, does not, to be sure, give results of high accuracy but is, nevertheless, sufficient to give the order of magnitude. The method was that of "the sag of a horizontal beam." (The theory of this method is discussed by Trouton, Proc. Roy. Soc. London, v. 77, p. 426, 1906.) The comparison material used was a glass of the same composition (lacking impurities) as one measured by English, namely, Na_2O 25 per cent SiO_2 75 per cent (curve No. 1 of Fig. 2). The actual operation consisted of preparing a rod or filament of albite-glass in an oxy-gas flame. A piece of the filament was laid across the rim of a platinum crucible about one cm in diameter and the whole placed in a furnace at a known constant temperature. The amount of sagging of the center of the filament in a measured period of time was observed. A filament of the standard sodium-silicate glass of the same diameter, as compared under the microscope, was laid across the same crucible and the rate of sagging at various temperatures was observed, until a temperature was found at which the rate of sagging was the same as that of the albite-glass at the different (higher) temperature. It was thus found that albite-glass at 1150° has approximately the same viscosity as the reference glass has at 640°, that is, approximately 10^8 poises. The method used does

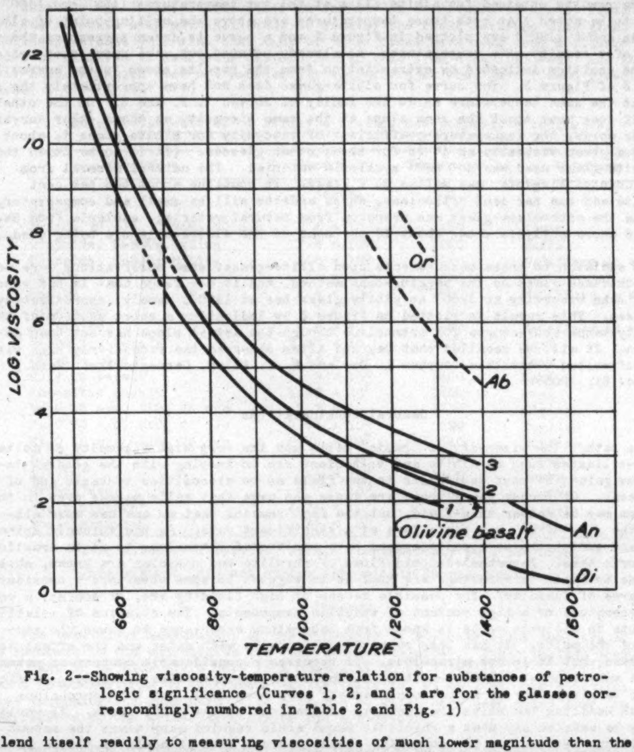

Fig. 2--Showing viscosity-temperature relation for substances of petrologic significance (Curves 1, 2, and 3 are for the glasses correspondingly numbered in Table 2 and Fig. 1)

not lend itself readily to measuring viscosities of much lower magnitude than the above, because the rate of sag is too great. With certain materials this difficulty can be obviated by carrying on the experiment in a liquid which, by its buoyancy, cuts down the force acting upon the beam. Such a procedure is not practicable with silicates at high temperatures. To measure the viscosity of albite-glass at a higher temperature the method was adopted of observing the rate at which a pyramidal fragment of the glass was transformed into a pool conforming to the shape of the crucible and having a flat surface. The method was again a comparison method, the rate for albite-glass being compared with that of the same reference glass. Since the force of surface-tension is an important factor in the phenomena observed, any great variation of this force would negative the value of the results. The surface-tension of silicate liquids does not, however, vary greatly with composition and temperature (in glasses closely related in composition to those under investigation a change of temperature of 300° makes only a 10 per cent change of surface-tension and substitution of a large proportion of one "basic" oxide by another makes a change of only about the same magnitude; Washburn, Shelton, and Libman, Univ. Ill. Bull., v. 21, No. 33, 1924) and it is probable that the rate of deformation or flow under the conditions is a reasonably close measure of the viscosity. By working in this manner it was found that albite-glass at 1400° behaved in the same manner as the reference glass at 850°, the indicated viscosity being therefore about 4×10^4 poises.

The results obtained for albite-glass at the two temperatures 1150° and 1400° (it is to be noted that both these temperatures are above the melting-point of albite, which is about 1120°) are plotted in Figure 2 and a curve is drawn suggesting the variation of viscosity with temperature. As already pointed out, the curve does not occupy the position indicated by extrapolation from the results shown in the curves 1, 2, and 3 of Figure 2. The curve for albite-glass does not have approximately the same slope at the same temperature as do the family of curves 1, 2, and 3. On the other hand, it does have about the same slope at the same viscosity as these other curves. In other words, the temperature-coefficient of viscosity for albite-glass is about the same at a given viscosity as it is for these other glasses. (It is to be noted that the albite-glass used was not pure synthetic material. The natural mineral from Amelia County, Virginia, was melted to a glass. It contains about two per cent anorthite and one per cent orthoclase, whose effects will be small and compensatory. Likewise the orthoclase-glass was prepared from natural material, adularia from St. Gotthard whose analysis shows about 12 per cent of the albite-molecule being used.)

In addition to these measurements upon albite-glass, some observations were made upon orthoclase-glass by the sagging-beam method, and it was found that it has sensibly the same viscosity at 1250° as albite-glass has at 1150°, namely, approximately 10^8 poises. This result is plotted on Figure 2 by indicating a short section of the viscosity-temperature curve for orthoclase though the actual slope has not been determined. It will be recalled that Day and Allen observed the excessively high viscosity of melted orthoclase (Arthur L. Day and E. T. Allen, Carnegie Inst. Wash., Publ. No. 31, 1905).

General considerations

The rather low viscosity of "basic" melts and the very high viscosity of molten alumino-silicates such as albite and orthoclase are in keeping with the general impressions gained by most geologists in the field as to viscosities of basic and of salic lavas. Of recent years there are those who urge that salic magmas even in the lava-form may be rather thin-fluid, but the fact remains that no one has ever witnessed the flow of any but basic lava at a significant rate. As the volcanic spine or as ash and pumice the more salic magmas have manifested themselves to us in eruptions of historic time. Nevertheless, old flows of rhyolite and obsidian are known, whose relations to their surroundings are such as to suggest to some observers a considerable degree of fluidity. The possible causes of high fluidity are, of course, a very high temperature or a high content of volatile components. The solution of volatile components in silicate melts is known from laboratory experience to lower the viscosity of the melts. It has been observed principally with water and the effect is very marked, but it is not miraculous. It requires a considerable content of water to reduce a very viscous silicate-melt to a condition of comparative fluidity. No figures can be given, for no actual measurements have been made, but the impressions gained in handling the melts are adequate indications of the above facts. It would probably be safe to say that a rhyolitic magma would require many times the amount of water ordinarily found in the congealed glass in order that it could be placed in the general class with basic magmas in the matter of fluidity. That a magma could retain such a proportion of water (and other volatiles) as it flowed freely upon the Earth's surface is difficult to believe, and that after coming to rest it could then lose the great bulk of this high water-content without giving evidence of that fact is almost inconceivable.

The other alternative, namely, that the magma was excessively hot, is perhaps not to be entirely excluded in some instances, yet in others the liquid was clearly within its crystallization-range as it flowed.

In the probable absence of a very high temperature or of a very high concentration of volatiles one cannot fail to question whether the lavas really had great fluidity. As bearing upon this question is the observed fact that typically these rhyolitic flows, that have been regarded as highly fluid, exhibit a glassy margin (with phenocrysts) whose thickness may be measured in feet. No one has ever seen a basic lava with a glassy margin of such proportions. If the viscosity of the rhyolitic flow were of the same general order of magnitude as that of basic lavas, it would be impossible to cool any significant mass of it to a glass, especially in the presence of crystals already formed.

Considering all the difficulties in the way of acceptance of highly fluid rhyolite it would seem most desirable to examine the field evidence with great care, with the possibility in mind that many of these flows have come from a fissure or a series of fissures of intricate pattern rather than from a central vent, and that their wide extension does not necessarily indicate that they have flowed great distances.

Table 3--Viscosities of silicate liquids and comparison substances

Substance	Viscosity	Temperature	Observer
	poises	°C	
Water	1×10^{-2}	20	
$MgSiO_3$ 70 o/o, $CaSiO_3$ 30 o/o	4×10^0	1430	Bowen
Diopside, $CaSiO_3.MgSiO_3$	7.8×10^0	1450	Feild
Diopside, $CaSiO_3.MgSiO_3$	3.8×10^0	1450	McCaffery et al.
$CaSiO_3$	4×10^0	1600	Herty et al.
$CaSiO_3$	2.4×10^0	1600	McCaffery et al.
Glycerine	1×10	20	
Anorthite	3.8×10	1550	McCaffery et al.
Nepheline basalt	7.97×10	1400	Kani
Olivine basalt	1.36×10^2	1400	Kani
Olivine basalt	1.19×10^2	1400	Kani
Andesitic basalt	1.38×10^2	1400	Kani
Na_2O 25 o/o, SiO_2 75 o/o	7.7×10	1310	English
Na_2O 25 o/o, SiO_2 75 o/o	2.71×10^5	790	English
Na_2O 25 o/o, SiO_2 75 o/o	6.25×10^7	650	English
Albite	10^8	1150	Bowen
Albite	4×10^4	1400	Bowen
Orthoclase	10^8	1250	Bowen
Rosin mixture[a]	4.36×10^7	10	Reiger
Rosin mixture[b]	1.32×10^9	10	Reiger

[a] This mixture is said to "spread spontaneously in a few days."

[b] This mixture "did not spread appreciably in one month."

Summary

The results of measurement of the viscosity of silicate melts that are of greatest interest to the petrologist are here brought together. These include measurements made by metallurgists upon such compositions as diopside and anorthite and some recent determinations by Kani upon remelted basalts, as well as determinations by glass technologists upon more salic mixtures to which have been added some new measurements by the writer upon albite and orthoclase.

The results of greatest significance are shown in tabular and in graphic form in Table 3 and Figure 2.

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FIELD EVIDENCE ABOUT THE VISCOSITY OF LAVAS

Clarence S. Ross

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There appears to be surprisingly little definite information on the viscosity of lavas. With few exceptions writers content themselves with such general and indefinite terms as "mobile", "viscous", or "highly viscous". Apparently the only attempts to actually calculate viscosity have been made on Hawaiian lavas.

G. F. Becker (Some queries on rock differentiation, Amer. J. Sci., 4th ser., v. 3, pp. 27-32, 1927) basing his calculations on the record of the 1840 flow at Kilauea which progressed eleven miles down a two per cent slope in two days, concluded that this lava had a viscosity about 60 times that of water.

More recently H. S. Palmer (A study of the viscosity of lavas, Hawaiian Vol. Bull., v. 15, No. 1, pp. 1-4, 1927) pointed out several errors in Becker's assumptions. In his calculations Palmer used formulas derived from experimental hydraulics and endeavored to evaluate all such factors as shape of channel, character of walls, slope, hydraulic ratio, and specific gravity of a gas-charged lava. He concluded that the viscosity was most probably about 15 times that of water but may have been as low as eight and as great as 20 times that of water.

Writers generally recognize that basaltic lavas are the least viscous, but a systematic discussion of field evidence presented by the different lava-types is commonly absent.

F. F. Grout (Petrography and petrology, p. 196, McGraw-Hill Co., 1932), although observing "magmas may be highly viscous, especially if they are siliceous and not hydrous," says, "Viscosity may also explain the relative scarcity of rhyolite flows, for the viscosity of siliceous magmas becomes high as it rises into cold cracks and loses mineralizers." This seems to be representative of a widely prevailing misconception about rhyolitic lavas. Alfred Harker (The natural history of igneous rocks, pp. 56-57, Methuen and Co., London, 1909), on the other hand, describes the high viscosity of andesitic material although he does not directly compare them with rhyolitic ones. He describes the extreme viscosity of the Pelee lavas which are andesitic, those of the same general type at Puy do Dome and Auverne, and the phonolitic ones at Velay. S. J. Shand (Eruptive rocks, p. 45, Thomas Murby, London, 1927) recognized that fluxes play an important part in reducing viscosity and says, "There is in fact a strong probability that the cessation of movement in a lava is due as much to the loss of gases as to the loss of heat."

The San Juan Region of Colorado and New Mexico, being one of the largest areas of volcanic rocks in the world to be systematically studied, presents interesting field evidence concerning the physical character of lavas. Here there is great extent, immense volumes, and wide diversity of lava types. The earliest series of eruption is dominantly andesitic in character, although fairly low in ferromagnesian minerals, and commonly carrying a little normative quartz. These have formed great dome-like masses that reach several thousand feet in thickness and that are many miles in extent. Wide spreading flows form a very minor part of the series and flow breccias are the most characteristic material.

The earliest andesitic series of eruptions were followed by others, each successive series being separated from the earlier one by a period of relative quiet during which there was profound erosion. The later series of eruptions tended to become more silicic, and more varied in character, and flow breccias less abundant. The intermediate eruptive periods were marked by latitic or rhyolitic types of lava, although subordinate andesitic material forms part of the series. The latites form fairly regular flows, and only rarely flow breccias.

The latest series of eruption were in general rhyolitic and basaltic in character, and appear to be very closely related in time. In some areas basalts were last and in others rhyolites. Basaltic eruptions began with olivine-basalt flows that spread as much as 25 or even 50 miles from their source. They were very regular in thickness and relatively thin. At the end of basaltic activity cones showing increasing evidences of explosive activity were built up, and the last flows rarely spread more than a few miles from their source. The rocks, although clearly belonging to the basaltic type, were commonly andesitic and even dacitic in character, but olivine-basalt cones were formed. The rhyolitic flows of the San Juan Region are very generally thin-bedded, wide spreading, and are almost comparable to basalt in this respect. Only near the end of rhyolitic activity were explosive tuffs, pumice fragments, and viscous glassy flows dominant and wide-spreading flows absent.

Although a relatively low viscosity in alkalic-silicic lavas may at times be in part due to a high superheat, it seems that it must be due largely to a concentration of volatiles. If volatiles are present in a potentially viscous magma in amounts sufficient to render them mobile enough to form even, wide-spreading flows, these volatiles must have been retained while extrusion was taking place. That is, they cannot have escaped immediately on the relief of pressure due to their arrival at the surface.

Basalts commonly contain vesicular cavities that are not elongated in the direction of flow, and it is not rare to see elongated vesicules up to many inches in length that stand in a perpendicular position, thus showing that even basalts have retained volatiles in solution until they came to complete rest, often many miles from the source. Although no doubt the water-content of pitchstones has at times been overemphasized, the undoubted existence of a high water-content in some of them shows that lavas of that type may become completely chilled while still retaining a notable water-content. It is evident that cooling, especially with crystallization, tends to expel most of the water, and so the water-content at the beginning of crystallization was no doubt higher and more general than analyses indicate.

In a magma of complex chemical composition it is evident that water and other volatiles are not simply dissolved as such in a silicate melt, but its atoms are united with other atoms of the magma in a great variety of chemical combinations of which we have a very limited knowledge. However, it seems evident that these volatiles are not released from these chemical combinations immediately on release of pressure. Only part of the many possible chemical combinations are potentially volatile, and those forming nonvolatile combinations must form new combinations before escape as a gas phase is possible. Under certain conditions, especially in silica-rich rocks, this appears to be a sluggish process that takes time, and particularly in rhyolitic lavas permits them to spread widely before the final escape of the volatiles that reduced their viscosity.

U. S. Geological Survey,
Washington, D. C.

A COMPARISON BETWEEN DIFFERENTIATION IN TWO KEWEENAWAN BASALT FLOWS AND THAT OF THE DISTRICT IN WHICH THEY OCCUR

T. M. Broderick

This communication was presented informally and no manuscript was prepared.

Calumet and Hecla Mining Company,
Calumet, Michigan

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AMERICAN GEOPHYSICAL UNION

Fifteenth Annual Meeting

SECTION OF HYDROLOGY

Washington, D. C., April 26, 27, and 28, 1934
Berkeley, California, June 20 and 21, 1934

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REPORT OF THE COMMITTEE ON SNOW, 1933-34

J. E. Church, Chairman

Organization

For the new triennium, the Permanent Research Committee on Snow has been reappointed with the recommended inclusion of G. A. Hathaway, Hydraulic Engineer for the Corps of Engineers, United States Army, to represent the Upper Missouri River Basin.

With this addition, the personnel and sphere or locality of special interest of each, as indicated in parentheses, are as follows:

J. E. Church, Chairman--Nevada Agricultural Experiment Station and Nevada Cooperative Snow-Surveys, Reno, Nevada
E. S. Cullings, Vice-Chairman--Black River Regulating District, Watertown, New York (Central Atlantic States)
Mathew Balls--Shawinigan Power Company, Montreal, Canada (British America)
H. T. Barnes--McGill University, Montreal, Canada (ice)
Paul L. Bean--Union Water Power Company, Lewiston, Maine (New England)
H. P. Boardman--University of Nevada, Reno, Nevada (Western section of Great Basin)
George Dewey Clyde--Utah Agricultural Experiment Station, Logan, Utah (Eastern Great Basin, especially Wasatch Mountains)
E. H. Collins--Washington Water Power Company, Spokane, Washington (Pacific Northwest, especially Upper Columbia)
E. B. Debler--United States Reclamation Service, Denver, Colorado (Southern Continental Divide, especially Colorado Basin and basins eastward thereof)
S. P. Fergusson--Harvard University, Blue Hill Observatory, Milton, Massachusetts (instruments)
Laurence M. Gould--Carleton College, Northfield, Minnesota (Antarctic)
G. A. Hathaway, Corps of Engineers, United States Army, Washington, D. C. (Northern Continental Divide, especially Upper Missouri Basin)
William Herbert Hobbs--University of Michigan, and International Commission on Glaciers, Ann Arbor, Michigan (International)
J. H. Ryan--Oregon Snow-Surveys, Salem, Oregon (Pacific Northwest, especially Oregon and Cascade Mountains)
Harlowe M. Stafford--California Department of Public Works, Sacramento, California (Pacific Coast, especially Sierra Nevada)

General considerations

The year has been one of progress rather than pause despite the counter elements that have been active due to financial need.

Official state cooperation has temporarily ceased in Nevada and California, the appropriation in the latter State having failed on reconsideration by only a narrow margin. However, in California all cooperating agencies have agreed to continue their individual snow-surveys and practically all of those in Nevada have done likewise. In Utah and New York the snow-surveys have been carried on as usual. In eastern Washington, because the precipitation has been above normal and the demand for power below the usual, the Washington Water Power Company has suspended their snow-surveys until the cycle changes.

On the other hand, a comprehensive snow-survey system is being inaugurated on the headwaters of the Missouri River in connection with Fort Peck Reservoir, built to improve flood-control and navigation on the upper Missouri. This Reservoir will impound from 17,000,000 to 22,000,000 acre-feet and in size and service duplicates Boulder Canyon Dam on the Colorado. The snow-survey will cover eight watersheds having a combined area of 57,000 square miles.

An immense storage-project serving the combined Sacramento-San Joaquin Basin has been authorized by the State of California, which should require the continuance of the California Cooperative Snow-Surveys for its best management.

In the State of Washington a commission has been authorized by the legislature to survey the State's natural resources, with probable attention also to the forecasting and prevention of floods.

In Nevada, the Agricultural Experiment Station has organized a cooperative project in the Humboldt Basin to improve forecasting of stream-flow in one of the most complex basins yet studied. The tortuous and blocked channel will be studied. Both State and Federal departments have joined in the task.

Regional reports

Greater details are given in the following regional reports by members of the Committee or others in close touch with conditions.

New England (Paul L. Bean)

(1) There is practically no cooperation in Maine between the State and local agencies carrying on snow-surveys or keeping records of depth of snow or corresponding precipitation. It can, however, be stated that all the power-companies and some of the water-districts in this State do, as a matter of record, gather information on the amount of snowfall and the water-content of the snow from time to time.

The major work along the lines of snow-surveying is carried on in the Androscoggin River Basin and in the Kennebec River Basin and is probably more fully developed in the Androscoggin River Basin than in any other section in this State.

Generally speaking, snow-surveys are made in this area on the first of every month and carried up until the spring break, the work being done very largely by men having control of the regulation of the streams. Inasmuch as I am in charge of the Androscoggin River Area, covering 3,000 square miles, much study has been put on the subject of snow-surveying in this Area by me and it might be of interest for you to know that on the first day of January, the first day of February, the first day of March and the 15th of March, and weekly thereafter until that condition obtains which we call "the spring break," indicated by the complete conversion of snow into water, a regular line of readings is taken from Lewiston, Maine, to the headwaters, a distance of approximately 180 miles, and covers elevations from about 200 feet above sea-level to about 2,500 feet above sea-level.

The maximum height of land on the watershed is probably around 5,000 feet, indicated by the land in the White Mountain Area.

The writer is also endeavoring to develop certain stations in the different kinds of growth which we obtain here, for the purpose of determining their effect on evaporation. To this end we are entering the Area at different points and laying off a section about 30 feet square which is carefully leveled up and then covered with light debris from the forest floor, generally in the form of leaves, etc. On this Area observers are taking daily readings of the depth of snow and the water-content of the same from the time the first snow falls in the fall until the snow has entirely disappeared off the ground. Much data have already been gathered together to give very interesting results, although I am of the opinion that more time is needed to draw any conclusions therefrom.

The surveying also takes another form, in that readings are taken at every 100-foot elevation along certain lines in the watershed, generally starting from a central control-point and going across the lowlands and directly up the mountains to the summit, wherever it is possible to reach them. This latter phase of the work has only been in progress about two years and sufficient information is not available, nor the lines sufficiently developed so that they can be carried clear to the summits of the mountains. I should judge that these lines will total at the headwaters probably fifteen or twenty miles which are traversed monthly. The main survey along the river valley is also taken monthly and covers about 160 miles. Development of this work is not going along as fast as I would desire, but we are making the most of our conditions and I think we are developing certain formulae which will enable us to estimate the runoff from these areas.

One big need at this time is the development of a technique to determine how much water passes from the snow into the ground. In other words, to get some measurement of the total volume of ground-water. The chief purpose of this is to make estimates of water available for river-regulation at the several power-plants and to determine magnitude of floods which may occur.

We have not during this past year established any new stations, but have opened up around five or ten miles of new lines on which readings can be taken and have been generally laid out with the idea of determining the effect of altitude on snowfall, as the new lines are laid out generally to ascend the side of the mountain, both on the windward and the leeward side.

(2) The present winter in this Area has been a most severe one with practically no precipitation in the form of rain. At the time of writing this report there has been almost a complete break-down in removal of snow and ice from the State highways and city streets. In fact, the removal of ice and snow from the State highways has only been in practice a matter of six or eight years and this is the first year that the equipment thereon has been brought to a test. I am inclined to think that the work done by the State has met the demands fairly well, but in the cities the equipment is being found quite inadequate.

(3) There is no work being done in connection with the scientific aspects of snow and ice, except along the lines of evaporation and to the best of my knowledge I am the only one carrying on this work. It seems to me that while I can detect something of the losses due to evaporation, still the equipment at hand is not sufficiently sensitive to classify this at the present time as scientific work, and I am just feeling my way along with the idea of developing some station equipment which will answer not only the question of evaporation, but the amount of water lost from the snow during the winter and spring months which passes into the ground.

I can assure you that in Maine at least there is a very strong and growing interest in the question of snowfall and water-content of the snow, and it is my best judgment that snow-surveys are absolutely essential in the intelligent regulation of rivers for power-purposes, for flood-control, and for the protection of property during floods.

New York (E. S. Cullings)

In the Adirondacks, the past winter has been characterized by alternating periods of mild weather and extreme cold with deficient precipitation. Record low temperatures were experienced at several stations during February. Precipitation was somewhat below normal during December and January, and only about one-third of normal during February. Runoff during the latter part of the winter was nearly as low as during the drought last summer. The accumulation of snow is little more than half the usual amount at this season.

The lowest temperature recorded for the winter was 60° Fahrenheit below zero. Several stations reported temperatures of from 52° to 58° below zero. The low temperature and deficient accumulation of snow resulted in the freezing of the ground in the Adirondack forest-land. From six to eight inches of frost were reported in various places. In the ordinary winter there is usually no frost in the ground when the snow-cover exceeds 24 inches. Ice in the Adirondack lakes at the end of the winter was from 24 to 27 inches in thickness.

No new lines of research were undertaken, because of limited resources of most of the cooperating parties.

Northern Continental Divide (G. A. Hathaway)

During the past five years I have been engaged upon investigations in connection with House Document 308 reports. As a result of our studies this office is now engaged in the construction of the Fort Peck Reservoir located near Glasgow, Montana, in the upper Missouri River Basin. The final capacity of the Fort Peck Reservoir has not been determined but it will be between 17,000,000 and 22,000,000 acre-feet and will be operated for maintaining certain required discharges in the Missouri River for navigation and the incidental development of hydroelectric power. Present plans contemplate drawing the Reservoir down during the spring months to store for the benefit of flood-control the heavy runoff from the snowmelt which occurs during May and June. The amount of the draw-down of the Reservoir will of course depend largely upon the snow in storage over the drainage-area above the Reservoir and in order to determine this more accurately I am at present outlining a program of snow-surveys. It is expected that courses will be established in at least eight tributary drainage-areas. The drainage-area above the Reservoir is approximately 58,000 square miles.

The work is of course under the supervision of the War Department and is to be paid for out of Federal funds.

Eastern Great Basin (G. D. Clyde)

A. B. Purton of the United States Geological Survey at Salt Lake City states "Snow-survey being carried out as usual." Prospects for water are discouraging over the entire intermountain region. We certainly are getting opportunities to study the Humboldt Basin during lean years but I hope the other kind will show up soon.

Western Great Basin (H. P. Boardman)

J. E. Church states that the snow-surveys have been requested even more than usual; all districts save one have joined in continuing them despite present cessation of State support. The Nevada Agricultural Experiment Station has joined in maintaining the routine snow-surveys for the research data thus obtained and has organized a large cooperative project for solving forecast-problems in the Humboldt Basin.

California (H. M. Stafford)

Present status of snow-surveying--Upon failure of the 1933 Legislature to continue the appropriation for snow-surveys, California's cooperative snow-survey project was discontinued on July 1, 1933. This has meant that until further appropriation is made, the State will be unable to supervise and head the work of the various cooperating agencies throughout the State nor will it be able to assemble and analyze all data and publish the same, together with forecasts of seasonal runoff, as in the past. Many of the cooperating agencies have agreed to continue with the surveys as established in the past and the State has therefore allowed the surveying equipment to remain with the cooperating agencies. The notes are filed in the State Office and will be available for future reference so that during the period of no official cooperation on the part of the State the records at least will not be a total blank.

The cooperating agencies continuing are as follows: Mt. Lassen Volcanic National Park--monthly survey of Mt. Lassen Course; Pacific Gas and Electric Company--key-surveys and main surveys at the end of March at all courses as in the past in the Feather, Yuba, American, Mokelumne, and Stanislaus River basins; Southern Sierras Power Company--main survey at the end of March at all courses as in the past in the Owens Basin; San Joaquin Light and Power Corporation--surveys as in the past in the San Joaquin and Kings River basins; Southern California Edison Company--surveys as in the past in the San Joaquin River Basin; Yosemite National Park--surveys at practically all courses as in the past in the Tuolumne and Merced River basins; Sequoia National Park--surveys as in the past at courses in the Kaweah Basin but discontinuance of surveys in Kings River Basin except possibly Rowell Meadow; Kern County Land Company--surveys in Kern River Basin to some extent (probably not as full a program as in the past); City of Los Angeles--surveys in Owens Basin as in the past.

The dominant purpose in all of these surveys is the determination of the seasonal water-supply which will be available for irrigation and for power-utilization.

No new units have been begun except for the work now being continued by the cooperating agencies as above outlined; the other work as previously established has necessarily been abandoned, temporarily at least.

The Central Valley Water-Project of the State of California was approved by a vote of the people of the State at a referendum election on December 19, 1933, and the project is now before Federal authorities for approval and financing. This project contemplates large storage on the upper Sacramento River and on the upper San Joaquin River and a coordinated use of the stored water for irrigation, power, navigation, flood-control, and control of salinity in the Sacramento-San Joaquin Delta.

With the final consummation of this project the coordinated regulation of the stream-flow to the best advantage of each form of utilization involved will necessarily require that there shall be available the best possible data with respect to the precipitation and snow-pack in each of the major stream-basins included in the Sacramento-San Joaquin drainage. With this requirement for efficient operation of the project, it would not seem too optimistic therefore to anticipate that its consummation will mean a return to active participation upon the part of the State in snow-surveying and allied investigations in the correlation of precipitation and snow with runoff.

Lassen Volcanic National Park

California has this year experienced unusually mild weather with a decided lack of snow at the lower elevations. But official snow-survey measurements taken April 4 in this Park indicate that an unusually heavy snow-condition exists at Lake Helen.

There is more snow, in fact, not in depth but in water-content, at the foot of Lassen Peak at this time than has existed on the survey-courses in any previous April since the first official measurements were taken in 1931.

Southwest (H. S. Colton, Director, San Francisco Mountain Zoological Station)

At our Laboratory, three miles north of Flagstaff, we kept a record of last winter's snowfall, using a section of stovepipe on a six-inch rain-gage. Each day the snow was melted and the water measured.

This year we wish to keep a record of the winter snowfall in the Inner Basin of the San Francisco Peaks at an elevation of 10,500 feet. We had been considering a six-inch tube about 12 feet tall. This station, from about November 1, 1934, when we will replace our rain-gage with a snow-gage, until about June 1, 1935, cannot be reached. We also plan to maintain a snow-gage at Wupatki National Monument, altitude of 5,000 feet, and one in Medicine Valley on the northeast side of the Peaks at an altitude of 7,000 feet. I thought perhaps your Mt. Rose sampler might help us.

During the summer rainy season we maintained 18 rain-gages about the San Francisco Mountains, but the problem of local snowfall rather stumps us.

Pacific Northwest, especially Upper Columbia (E. H. Collins)

I feel quite apologetic relative to my activities on your Committee. However, the Washington Water Power Company has accomplished no snow-surveying since 1932 with the exception of a volunteer survey on one course in the Bitter Root Mountains at the head of the Coeur d'Alene River. We now have twelve years' record on this course. A tabulation of this record is given in Table 1, and I call your attention to the fact that the years 1924 and 1925 are missing.

Table 1--Sunset Snow Course (elevation 5,600 feet)
Bitter Root Mountains, Coeur d'Alene River drainage
water-content of snow in inches on March 15

Year	Water-content	Year	Water-content	Year	Water-content	Year	Water-content
1921	31.6	1926	25.8	1929	21.8	1932	33.2
1922	28.7	1927	32.9	1930	21.9	1933	47.9
1923	36.3	1928	30.9	1931	20.3	1934	39.6

You will note that the snow-cover in the last three years has been above normal. This fact in general can be determined without a snow-survey. Since power-demands have been below normal, there was no economic use for snow-surveys. I would be glad to hear of any discussion in your Committee that would indicate that surveys in above normal years would enhance the economic value of snow-surveying. So far we have had to admit that the above normal years' data would be interesting from a scientific point of view but of no value economically. It is the intention of the Company to resume snow-surveying as soon as economic value is apparent.

E. W. Allen of Seattle, Washington, Officer of the Mountaineers, reports "The last Legislature passed an act creating a State Survey Commission. Inasmuch as I made the original draft of this act you will appreciate that I am taking a considerable interest in this Survey. One of the matters which will probably be looked into is a public-works program which among other things will deal with flood-control."

British America (British Columbia, J. C. MacDonald, Comptroller of Water Rights)

Status of snow-surveys--I do not know of any actual snow-survey work which has been done in this Province. The British Columbia Electric Company, which supplies hydroelectric power to the lower mainland of British Columbia, has up to the present depended entirely on precipitation-records for forecasting runoff. The West Kootenay Power and Light Company, which supplies the main demand of the interior of the Province, has only recently become interested in the total season runoff. For the last two years it has depended, to some extent, on the reconnaissances made by the aeroplanes of its allied Company, the Consolidated Mining and Smelting Company. It finds that the presence or otherwise of snow on certain specific points in the mountains gives them quite a fair indication of the runoff-conditions.

The Government of the Province has done nothing as yet. The Provincial estimates of expenditure for the coming fiscal year are now under consideration, and will go before the Legislature within the next two weeks. I have asked for, and have reasonable hopes of getting, an appropriation for general water-surveys, which will, if granted, be spent in part on setting up a series of lines in various parts of the Province. It will not be possible to secure any records of snow-depths this season, but it is hoped that we may be able to make the necessary preparations for a beginning next year.

The conditions on the Coast Region are excellent. The precipitation during April to July is very small compared with that of the balance of the year. In the interior of the Province the conditions are not nearly so good, but I am of the opinion that, even there, the snow-survey will be of decided value to us. For a number of years now we have regulated the yearly seasonal levels of one of our large storage-basins by observation with the snow-depths at one easily accessible point in the hills, and have had much better results than before that method was started. This applies to one of our worst localities.

If I am able to carry out my proposals, I shall develop some lines across the drainage-basins of the Coquitlam and Stave rivers, the main source of supply of the British Columbia Electric Company. These streams are tributary to the lower Fraser River. I shall develop other lines across the Okanagan Valley and across the valleys of the headwaters of the Columbia and Kootenay rivers. All these latter streams are part of the Columbia River System, and our records may later be of value to the power- and irrigation-interests along that stream in Washington.

The West Kootenay Power and Light Company has recently constructed a dam across the Kootenay River near the outlet of Kootenay Lake, the primary object of which is the development of power. This dam will, if the permission of the International Joint Commission is given, be used to regulate the low-water levels of Kootenay Lake and maintain a storage which will increase the low-water flow of Kootenay River, and therefore of the Columbia, by some 5,000 cubic feet a second. The surveys at the headwaters of the Kootenay are intended to assist in the regulation of this storage.

Progress in snow and ice removal--Snow is not a problem in the heavily-settled Coast areas of British Columbia. On the Coast Section there are no arrangements or equipment for snow-removal except at one or two winter-resorts in the hills. The main lines of the railroads follow water-grades and have little or no snow-troubles until they reach the main Rocky Mountains. The Kettle Valley Branch of the Canadian Pacific Railway is the only line near the Coast which has snow-difficulties. There was a very heavy precipitation on the Coast Divide across this line, and during the past winter the Road has been entirely out of commission, in spite of the excellent snow-removal equipment maintained. The main line of the Canadian Pacific has its problems in the vicinity of Revelstoke, and from there throughout its passage through the Rocky Range. The five-mile Connaught Tunnel through the Selkirks has been a big feature in eliminating the Canadian Pacific Railway's main difficulties. One or two stoppages of short duration have occurred during the past year.

The Provincial Public Works Department maintains quite elaborate snow-removal equipment between the Town of Quesnel and the mining settlement of Barkerville, a distance of about 60 miles in the northern reaches of the Fraser River System. The Department has been successful this year in maintaining communications in spite of an unusually heavy snowfall. This is the only road-clearing work worthy of mention in the Province.

British America (Mathew Balls)

As to the present status of snow-surveying in Canada, there has been no marked progress during the past year, but work previously undertaken by the Federal Government and also by private companies has been continued as follows:

Federal cooperation--(1) Snow-surveys at the headwaters of the St. Mary River are still being carried out jointly by officers of the United States Geological

Survey and the Dominion Water Power and Hydrometric Bureau for the purpose of forecasting stream-flow. For the 12 years of survey, the estimates average 4.4 per cent higher than the actual runoff of May, June, and July. New equipment in use during the last two years seems to give results higher than the present curve.

(2) Snow-surveys at the headwaters of the Winnipeg River have been continued by the Dominion Water Power and Hydrometric Bureau in connection with the regulation of the Lake of the Woods and Lac Seul reservoirs. For the six years the snow-survey has been carried on, the results have given an accurate check on the accumulated winter precipitation worked out from the network of meteorological stations located throughout the Area. However, the relation of April and May runoff to accumulated winter precipitation, that is, November to February, inclusive, varies all the way from 23 per cent to 134 per cent, the long-term average being about 60 per cent, and the average of seven highest years 74 per cent.

(3) The Government has not carried out or cooperated in snow-surveys at the headwaters of the Bow River or any other watersheds on the Eastern Slope of the Rockies within recent years.

Power companies--Apart from two power companies operating in the Province of Quebec, there do not appear to be any other Canadian companies or organizations carrying on snow-surveys in connection with the studies of stream-flow. The other two power companies referred to are the Gatineau Power Company, with three power-developments aggregating 470,000 horse-power on the Gatineau River, and the Shawinigan Water and Power Company, with four developments aggregating 834,000 horse-power on the St. Maurice River.

The Gatineau Power Company has carried on snow-surveys since 1928 in the Gatineau River Watershed. The results, however, appear to have been more or less problematical on account of important factors other than water-content of snow which must be considered in the forecasting of stream-flow. The Company consequently finds it difficult to estimate the degree of accuracy obtainable in forecasts of spring runoff based upon the results of snow-surveys.

The Shawinigan Water and Power Company has carried out snow-surveys during the month of March in each year since 1928. Snow-courses of approximately one mile in length were established for this purpose in the St. Maurice Watershed at Shawinigan Falls, La Tuque, Manouan, and Oskelaneo River. While the results of these surveys show a relationship between the water-content of snow-cover in March and the natural runoff during the ensuing months of April, May, June, and July, this relationship is undoubtedly affected by other factors which must be studied before reliable forecasts can be made. These factors include precipitation in late autumn, as affecting ground-conditions prior to the freeze-up, the nature of the spring thaw, and departures from normal precipitation during the period of spring runoff.

A comparison of the water-content of the snow, as determined by the March surveys in each year, and the actual runoff, as computed from observed regulated flow, during the ensuing months of April, May, June, and July in each of the years 1929 to 1933 is given in Table 2.

Table 2--Water-content of snow and actual runoff in percentage of normal

Year	Water-content of snow	Actual runoff
1929	118	114
1930	107	115
1931	91	73
1932	73	76
1933	167	89

A study of the factors, other than the water-content of snow, which necessarily enter into the problem of forecasting stream-flow, is being made in an endeavor to account for such a wide divergence as occurred in 1933 in the relationship between water-content of snow and the actual runoff.

Publicity

The answers to the Questionnaire (see Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 340-341) are being slowly tabulated.

The list of colleges and schools in the United States and Canada giving courses in hydrology with a classification of the courses given at each institution is now ready for publication.

An address-list is being prepared of all organizations and individuals interested in snow-surveying. This list will be made as complete as possible in order to facilitate the mutual distribution of information.

The biography of snow-surveying has been published in Geographical Review (October, 1933) under the title "Snow-surveying: Its principles and possibilities." This has awakened much interest and brought many inquiries.

The "Proceedings of the Western Interstate Snow-Survey Conference" is being published by the Nevada Agricultural Experiment Station, which acted as host to the Conference.

The large monograph on snow being prepared by this Station has entered upon the stage of publication, which will proceed only slowly because of the necessity of accumulating funds for its printing.

As an innovation, a chapter on snow-surveying is being included in the revised edition of Davis and Kelley's text on "Surveying".

The radio has also come into use. Over the Western Division, National Broadcasting Company, during the Western Farm and Home Hour, a series of talks has been given by the Chairman--one each year. Last year, "The biography of snow-surveying"; the present year, "Snow-surveying and the Boulder Canyon Dam"; early this coming year, "A snow-survey system for the Columbia Basin."

The many calls for information emphasize the need of guidance and information for the steady and straightforward growth of snow-surveying.

Western Interstate Snow-Survey Conference

Following the initial meeting of the Western Interstate Snow-Survey Conference in February 1933, a Supplementary Conference was held also at the Nevada Agricultural Experiment Station on June 28, 1933, at the request of Southern California representatives who had been blockaded by snow from attending the earlier meeting.

The program of the Conference consisted of the following practical questions which had arisen in connection with snow-surveying and forecasting runoff in the Owens Basin, California:

(1) Can a series of streams be estimated according to a standard, or must each be a problem of itself?
(2) Would not a master-station, maintained and operated by the State, be more desirable than the present supervision over the cooperative agencies in giving satisfactory answers to technical points and inquiries?
(3) What is the best method, if any, of determining the long-time effect of dry years upon the runoff, soil-capacity, and similar related items?
(4) Has any method been devised for determining capacity in a satisfactory manner for snow-surveys?
(5) What is the effect of wind, temperature, rain, topography, viscosity (porosity), and soil-temperature, and what method will best adapt itself for their determination from a practical standpoint?
(6) How much variation in time is permissible in consecutive years in making snow-surveys to still get comparable results?
(7) What is the practicability of long-period snow-recording devices being designed for regions remote from habitation?

Much discussion was also given to improvement of apparatus.

Cooperation

Cooperation in all fields has been active and pleasant. The following represent new developments:

The new Chief of the United States Weather Bureau has written of his plans to revise the snowfall-work in the mountains of the West and desire for the Committee's advice.

The Utah office of the Division of Crop and Livestock Estimates of the United States Department of Agriculture is requesting intermountain snow-surveys in connection with forecasting agricultural production.

The Committee on Snow has found opportunity for practical cooperation with the Committee on Glaciers by furnishing data on the elevation of maximum snowfall in the Sierra Nevada in connection with the study of Pleistocene glaciers. Mr. Matthes writes: "The establishment of a zone of maximum snowfall on the Sierra Nevada would be of utmost importance in connection with my geomorphologic studies in the range."

The Western Division of Hydrology is acting as patron to the Western Interstate Snow-Survey Conference, which will hold joint meetings at the Western sessions of the American Association for the Advancement of Science.

The Committee on Snow also has been asked by the Committee on Evaporation to prepare data on evaporation at high altitudes and latitudes in connection with the joint session, in April 1934 at the Union's fifteenth annual meeting, of the sections of Hydrology and Meteorology.

Research

Two large research-projects have been started in the present year, namely, (1) the effect of forest on the accumulation and melting of snow and (2) the improvement in forecasting runoff in the Humboldt Basin, Nevada. A third research proposed for publication by E. H. Collins is "The relation of runoff to degree days above freezing." The data of these three problems are briefly as follows:

(1) The effect of forest on the accumulation and melting of snow on the west slope of the Sierra in California, by the Division of Forestry of the University of California under direction of Joseph Kittredge, Jr., Professor Forestry--"A project has been started this winter on the Stanislaus River drainage at elevations between 5,000 and 6,000 feet to attempt to learn something of the effect of different kinds, sizes, and densities of forest-cover on (1) the accumulation of snow as affected by the tree-crowns, (2) the current-changes in the water equivalent of the total snow on the ground, and (3) the evaporation and water-yield from the snow as it melts. Courses of sampling points have been established and records are being obtained under the following conditions: (a) In an open meadow; (b) in a cut-over slashing; (c) in mature ponderosa pine; (d) in dense sapling ponderosa pine; (e) in dense medium-size white fir; (f) in old less dense white fir; (g) in mature mixed ponderosa and sugar pine; (h) in cut-over mixed conifer; and (i) in mature red fir. A series of mechanically-spaced sampling points have been laid out in each condition. Records are being obtained currently by means of snow-boards, snow-sampling tubes, and evaporation-pans, perforated to allow water to pass down into a container for separate measurement."

(2) Improvement in forecasting runoff in the Humboldt Basin, Nevada, by a cooperative Committee of State and Federal agencies led by the Nevada Agricultural Experiment Station. The three dominant problems are (a) the waste due to low temperature during melting, (b) the effect of precipitation or its lack during runoff, and (c) the absorbent power of deep alluvial soils. From $3000 to $4000 annually will be spent by all agencies cooperating in the work.

(3) Relation of runoff to degree days above freezing, by E. H. Collins, Washington Water Power Company--"I was interested in the subject of meteorology in high latitudes and high elevations. Some years ago we made a study of the relation of runoff to degree days above freezing. This led to a desire to have more temperature-data at higher elevations. The underlying factor of this study is that with temperatures at or below freezing no runoff occurs. Also the temperature-data had some relationship to precipitation, evaporation, and percolation which are factors affecting runoff. I am enclosing herewith prints of studies of this nature made on three watersheds covering seven years' data. You will note that the climatic year starting November 1 was

used. This is about the time of the first snows at higher altitudes. The highest temperature-station in these studies was at elevation of 5,200. The lowest part of the drainage-area is elevation 2,200. The 'Weighted monthly summation for a year of degree days above freezing' plotted on the curve consists of a summation of degree days above freezing weighted as to elevation and is plotted against the per cent of annual runoff accumulated by the same date. After the curve is established the degree days above freezing are computed say to January 1. The curve indicates that some per cent, say 10 per cent of the annual runoff, has occurred. The gaging station gives the runoff equal to 10 per cent and 100 per cent is the total runoff and indicates a wet or dry year. It was found that after receiving 30 to 60 days' record of temperature and runoff, or by January 1, a fair prediction could be made as to the succeeding summer runoff. I offer you the above discussion for such value as it may have in your Committee work, and if it seems desirable I will be pleased to assist by preparing the material in more detailed and finished form."

Bibliography of ice and snow

The Section of Hydrology has now taken active measures to compile a bibliography of hydrology. However, the original plan of the Committee on Snow to compile a bibliography of snow and ice is still little more than dormant, though its plans still continue to grow.

Professor Barnes of the Committee is actively compiling the bibliography on snow and A. A. McCoubrey, Honorary Editor of the Canadian Alpine Journal, has generously offered to compile a bibliography of snow and ice from this Journal, with a critical abstract of each paper. This Journal covers 26 years.

Professor Clyde and Professor Boardman have also undertaken to abstract the agricultural and civil-engineering journals. Still other volunteers are needed. Dr. W. H. Hobbs and R. E. Horton are reporting current literature. Hazel Miller, graduate student at the University of Chicago, who has had experience at Blue Hill in bibliographical work in meteorology, has been studying Russian to equip herself for one of the most prolific fields in the hydrology of ice and snow. Appropriations are vitally essential to pursue some of the foreign branches of this subject.

International organization

(a) International Commission of Snow--The recommendation of the American Geophysical Union to the International Association of Scientific Hydrology that an International Commission of Snow and Ice be organized was favorably considered at the triennial meeting at Lisbon in September 1933. Thus the effort of Dr. Meinzer, when Chairman of the Section of Hydrology, has reached fruition. An International Commission of Snow was authorized with the American Chairman as President of the Commission. The division of the fields of snow and ice was left to the Commissions of Glaciers and Snow for adjustment. The following letter of Dr. Paul Louis Mercanton, Secretary of the International Commission of Glaciers, is most generous and leaves the field of snow and seasonal ice, even in the Polar regions, to the International Commission of Snow, reserving only the study of glaciers throughout the world as its special field. The study of the alimentation of glaciers is left for the present as neutral ground.

> "First of all I beg to be excused for having made you wait so long for my reply, but the fact is I have been overburdened with pressing duties. Here are my personal ideas concerning the question:
>
> "The old Commission of Glaciers was created in 1894, for the sole purpose of realizing a check on the variations of glaciers throughout the entire world and not for any further purpose. Besides, it has not occupied itself with any other matters.
>
> "When Messrs. Hamberg and Reid, together with myself, worked to replace that Commission which the World War had almost completely destroyed, by a new one, it was with exactly the same end in view, and we did not think at that time to attribute to it a broader task. Its field of activity is already sufficiently difficult to exploit. As a matter of fact, certain members of the Hydrological Association desired to widen its scope, and that was precisely in the direction of measurements of permanent or temporary snowfalls.
>
> "For the Commission on Glaciers only the snowfalls over periods of years have an immediate interest in relation to the level and volume of the glacial collector.

The seasonal snowfall and the snow outside of the immediate terrain of the glacier, are of less interest.

"It is possible that our Commission may some time extend its activity to the variations of névé (that is, glacier-snow or 'perpetual snow'), a matter of which it cannot be deprived, but at this time an arrangement with the Snow Commission is easy to enter into. Therefore, give to your program such extension as you may see fit in line with your project.

"The question of temporary ice, lakes, rivers, etc., may very readily be included in your domain. There is also no objection to including the question of polar ice.

"To sum up: I believe I am following out the idea of the present Commission on Glaciers by limiting its task to the observance of variations in world glaciers, it being clearly understood that one cannot prohibit it from occupying itself with the alimentation and ablation of glaciers if it regards it as useful to its task to go into these questions. However, it does not intend to reserve unto itself a monopoly in this line and will be thankful for every collaboration or parallel activity with this aim in view."

The following brief note by Professor Diénert, Secretary of the International Association quotes Dr. Mercanton to the same effect but emphasizes the vastness of the field:

> "Dr. Mercanton has informed me that he has written you February 25, 1934. In his reply he has indicated to you that the Commission on Glaciers controls solely the variations of glaciers in the entire world. You have then a vast domain to explore when the Commission of Snow shall have been organized."

To assure the closest and most generous cooperation possible, Dr. W. H. Hobbs, who is Vice-President of the International Commission on Glaciers, has been asked to serve as a member also of the International Commission of Snow. Robert E. Horton, whose national and foreign interest in all forms of hydrology makes him especially valuable as a general member, has consented to aid.

The Commission is now being organized as rapidly as great distances will permit. Not only the snow and ice countries of the Northern Hemisphere will be included but also Argentina, Australia, and India. Special representatives will be sought for the hydrology of snow, snow-removal, the economy of avalanches, the alimentation of glaciers (especially of the Polar Ice-Caps), ice-engineering, sea- and harbor-ice (particularly Polar), and the Polar Ice-Caps. Instruments will also be included. Unfortunately, conference must be had mainly through letter correspondence.

A full report of the organization of the Commission with projects then under way will appear in the next annual report of the American Committee. The first suggestion so far made is that completer reports of snowfall be urged throughout the world.

(b) International Congress of Ice and Snow--Since the International Commission of Snow was organized at Lisbon, the following invitation has come from the Fourth Hydrological Congress of the Baltic States, held in September at Leningrad, to attend an International Congress of Ice and Snow at Helsingfors, Finland, in 1936:

"Warsaw, Poland, November 24, 1933

"Having learned of your fine initiative in organizing ice-studies, I take the liberty of communicating to you the following:

"The Fourth Hydrological Congress of the Baltic States, held in September, 1933, at Leningrad voted, among its different resolutions, two concerning ice-studies: (1) The need of an International Organization for these studies and (2) the appointment of a Committee for the Fifth Congress to be held at Helsingfors, Finland, in 1936.

"Having been called upon to look after the realization of the projects, I take the liberty (in view of my having made the motions for these resolutions) of presenting to the Committee of the 1936 Conference the following resolutions:

> 'That an International Congress of Ice-Investigators be convoked at Helsingfors in 1936 simultaneously with the Fifth Baltic Conference by the aforementioned Organizing Committee. This is to confer, in this connection, through the agency of the curators of the Baltic Conference, with the Hydrological, Hydrotechnical, Meteorological, and Geographical institutions of the Baltic States, and also directly with those of Norway, The Netherlands, France, Switzerland, Austria, Hungary,

England, the United States, Canada, and Japan, inviting them to nominate their delegates.'

"This Congress will be in a position to bring to reality an international organization for ice-studies as postulated in the Fourth Conference, and especially to found the edition of a new encyclopedia as well as to establish an international review (cf. Annex).

"As most of the ice-investigators are from the Baltic countries and will therefore be in large part members of the Fifth Baltic Conference, this Conference will offer the best opportunity as well as the most practical means, of convoking the International Ice Congress.

"I take the liberty of sending you by this mail: (1) The text of the resolutions voted in the Fourth Conference; (2) plans for a circular letter and a classification of the problems to be taken up at the Ice Congress of 1936; (3) excerpts--in addition to my two reports to the Fourth Baltic Congress (I call your attention to the report No. 97); (4) a copy of my 'Natural History of Ice' in Polish with a supplement in French, followed finally by an 'ice-bibliography' which is complete up to 1916 and almost complete up to 1922.

"Believing that my American colleagues will not fail to take part in three years, in the First Ice Congress, I am,

Very cordially yours, Antoni Boleslaw Dobrowolski,
Permanent Director of the Central Meteorological Institute of Poland and Member of the Belgian South-Polar Expedition of 1897-1899"

The "Annexes" referred to in the above letter are:

Fourth Hydrological Conference of the Baltic States, 1933--Text of the resolutions voted concerning the International Organization of Ice-Studies and of the phenomena related to ice:

(1) In view of the fact that ice, because of its universality and particularity, has been studied for a long time by the most diverse specialists, and the works concerning ice being scattered through the most diverse publications, the Fourth Hydrological Conference believes to be necessary (a) the publication of an encyclopedia of international scope and dealing with ice, with the phenomena associated with ice, with its utilization and the struggle against it, together with a complete bibliography, and (b) the foundation of an international review dedicated to the above-mentioned subjects.

(2) In view of the importance of the problems relative to ice-study on an international scale, the Conference believes desirable the creation of an international organization dedicated to the aforementioned problems.

Ice-Congress of 1936--(I) Plan of the circular letter to be sent to the hydrological, hydrotechnical, meteorological, and geographical institutions of the Baltic States, Norway, Netherlands, France, Switzerland, Austria, Hungary, England, United States, Canada, and Japan deposited with the Organizing Committee of the Fourth Hydrological Conference of the Baltic States is as follows: The Fourth Hydrological Conference of the Baltic States, held at Leningrad in September, 1933, having, by unanimous vote, recognized the theses of the Ice Commission affirming the need of an international organization of ice-studies and of the phenomena associated therewith, and particularly the need, in this domain, of a new encyclopedia as well as of an international review, the Organizing Committee of the Fifth Conference, being called upon to seek means for carrying out these resolutions, has decided to convoke an International Congress of Ice-Investigators to be held on the same date and place as that of the Fifth Conference, i.e., the month of ----- 1936 at Helsingfors, and requests you to please delegate your specialists.

Ice-Congress of 1936--(II) Project of the classification of problems (groups and commissions) assigned by the Organizing Committee of the Fourth Hydrological Conference of the Baltic States: (1) Commission for an international organization for ice-studies as well as of the phenomena related with ice; (2) general section including (a) physical, chemical, and crystallographic properties of ice and (b) crysophere (compare A. B. Dobrowolski's report to the Fourth Baltic Conference No. 97) as a unit and the interdependence of the different components of the same; (3) section dealing with the atmospheric ice and the phenomena related thereto including (a) ice-clouds, ice-fogs, and optical phenomena related thereto [snow, sleet, hail, ice-rain, frozen dew, white frost, hoarfrost, glazed frost, icicles, natural ice-houses, stalactites, and stalagmites of ice], (b) snow-cover and snow-line, and (c) glaciers, especially polar glaciers; (4) section dealing with ice on waters and with the phenomena related thereto including (a) ice on rivers, (b) ice on lakes and ponds, and (c) ice on the sea--especially ice on the polar seas; and (5) section dealing with frozen ground and the phenomena related thereto.

This invitation includes evidently only the countries of the North. Favorable reply has been sent with suggestion of cooperation. Formal acceptance by the United States has been recommended to the American Geophysical Union. [Favorable action, following the recommendation of the Section of Hydrology, was taken at the General Assembly of the Union, April 27, 1934, and J. E. Church was designated as delegate from the American Geophysical Union.] The Committee's letter, signed by J. E. Church as President of the International Commission of Snow and Chairman of the Permanent Research Committee on Snow of the American Geophysical Union, in reply concluded with the following paragraphs:

> "You, on your part, are organizing an International Association on Ice both seasonal and glacial and on snow-fields as a subordinate division of the subject, thus putting the emphasis upon the great ice of the Polar regions and the ice-coverings of the great rivers and seas. I am greatly attracted to your work and shall be glad to send announcement of your plans of organization in 1936 to all the members of our American Committee and also to the members of the International Commission of Snow which we are organizing not only in the countries of the Northern Hemisphere but also in Argentina, India, and Australia. There should be no difficulty in the International Commission of Snow and Seasonal Ice cooperating with your International Organization on Ice and its phenomena, for the emphasis of the two organizations will be different.
>
> "Regarding delegates from America, how many would you desire appointed for your coming conference in 1936 at Helsingfors? Your plan of publishing an encyclopedia seems good if it can be afforded financially, but your International Review is possibly more feasible owing to its smaller expense. Unfortunately, at the present time, even 'Arktis,' the magazine of Aeroarctic, has been suspended. The American Geophysical Union is now attempting to compile a bibliography on Hydrology including snow and ice. It is even trying to arrange for a magazine in which to publish its papers. So far only the Transactions have been published.
>
> "Please keep me in touch with any further developments in connection with your plans and in return I will send you both our organization and plans as they develop. In three years' time much should be accomplished."

Current publications

The list of current publications for the present year has been furnished mainly by Dr. W. H. Hobbs, Robert E. Horton, and Dr. Howard T. Barnes. As in 1932-33, the list is broad in order that interest may thereby be widened. As other sources of bibliography appear, the list will be correspondingly narrowed.

Snow

(1) General--

- V. Conrad und M. Winkler (Wien), Beitrag zur Kenntnis der Schneedeckenverhältnisse in den Österreichischen Alpenländern, Beitr. Geophys., v. 34, Köppen- Band III, pp. 473-511, Leipzig, 1931.
- E. Hess, Races de pins et bris de neige, J. Forest. Suisse, v. 84, pp. 269-277, 1933.
- J. B. Kincer, What makes it rain, Tycos, April 1933, p. 65.
- N. N. Kalitin (Sloutzk), Die Strahlungseigenschaften der Schneedecke, Beitr. Geophys., v. 34, Köppen- Band III, pp. 354-366, Leipzig, 1931.
- Literary Digest, How driven snow cuts, v. 115, p. 24, February 4, 1933.
- Harold E. Miner, How scientist-detectives solved the mystery of the yellow snow, Tycos, January 1933, p. 17.
- Robert S. Monahan, Mount Washington reoccupied, Stephen Day Press, Brattleboro, 1933.
- C. Moran, Manufacturing snowflakes, Tycos, April 1933, p. 56.
- V. Paschinger, Die Schneegrenze in verschiedenen Klimaten, Petermanns Mitt., Ergänzungsheft 173, Gotha, 1912.

Snow--Continued

(1) General--Continued

G. Etzel Pearey, Il Neige, Bull. Amer. Met. Soc., January 1934.

Marie Widmer, When winter abides in Switzerland, Tycos, January 1933.

(2) Snow-surveying--

J. E. Church, Snow-surveying--Its principles and possibilities, Geog. Rev., October 1933.

J. E. Church, Preliminary report of Cooperative Committee on Humboldt Basin, Nevada Agricultural Experiment Station.

J. E. Church, Snow-surveying and the Boulder Canyon Dam, radio broadcast over Western Division, National Broadcasting Company, March 30, 1934.

Gene Day, Uncle Sam ferrets new facts about snow, Tycos, January 1933, p. 29.

Carl Elges, Forecasting the 1933 runoff in the Humboldt Basin, Nevada--A study in Great Basin hydrology, Bull. Amer. Met. Soc., February 1934.

E. S. Cullings, Snow-conditions in Adirondack Region, winter of 1933-34, Black River Regulating District, Watertown, New York.

H. P. Boardman, George Devore, and Leigh Sanford, Report of Nevada cooperative snow-surveys, April 1, 1934.

Carl Elges and J. E. Church, Report of Nevada cooperative snow-surveys, Humboldt Quadrangle, March 1, 1934.

Nevada Agricultural Experiment Station Report, Excerpt in Bull. Amer. Met. Soc., April 1933.

Davis George, Saving rainfall by providing proper soil-storage, Tycos, April 1933, p. 61.

Utah--Water-supply forecast for Utah, George D. Clyde, April 1, 1934, Utah Agricultural Experiment Station.

Western Interstate Survey Conference, Proc. Nevada Agricultural Experiment Station, 1934.

(3) Snow-removal--

Snow-removal in the winter of 1933-34--Hand labor to relieve unemployment, or machines to aid re-employment?, American City, v. 48, pp. 53-54, September 1933.

Snow-removal experiences in American municipalities, American City, v. 48, pp. 59-60, October 1933.

Snow-removal in the United States, American City, v. 48, pp. 52-53, November 1933.

Snow-removal experience in Elkhart County, Indiana, H. A. Firestone, American City, v. 48, p. 49, August 1933.

Removing snow from highways, Tycos, April 1933, p. 59.

Ice

(1) General--

T. C. Barnes, and T. J. Jahn, Effect of ice and steam-water on Euglena, Proc. Nat. Acad. Sci., v. 19, p. 638, 1933.

T. C. Barnes and E. J. Larson, Further experiments on the physiological effect of heavy water and ice-water, J. Amer. Chem. Soc., v. 55, p. 5059, 1933.

R. Chambers and H. P. Hale, The formation of ice in protoplasm, Proc. R. Soc., B, v. 110, p. 336, 1933.

Lennox Kerr, Ice, London, Lane, 1933.

E. L. Kinsley and O. L. Sponsler, Molecular structure of ice and liquid water, Proc. Phys. Soc., v. 45, p. 768, 1933. [Theoretical paper.]

G. Oplarka, Space-charges in ice, Helv. Phys. Acei., v. 63, p. 198, 1933. [Relating to the anomalous dispersion of the dielectric constant of ice.]

How ice-flowers are formed, Tycos, January 1933, p. 20.

(2) Sea- and river-ice--

F. I. Bydin, Ice-formation under natural conditions, Izvestiya Nauchno-Issledovatelskovo Instituta Hydrotechniki, v. 4, pp. 175-181, 1932. [Graphical records of three years' observations on formation and growth of ice-floes in Svir River in northern European Russia; mathematical formulae for computation of thickness of ice, and winter discharge of freezing rivers; in Russian, with brief English abstract.]

Albert Defant, Eisberge und Eissicherungsdienst im Nord Atlantischen Ozean, Polarbuch, Mittler, Berlin, 1933, pp. 55-84.

The menace of icebergs, Tycos, July-October 1933, p. 110.

Ice--Continued

(2) Sea- and river-ice--Continued

F. I. Bydin, Nature of anchor-ice, Isvestiya Nauchno-Issledovatelskovo Instituta Hydrotechniki, v. 5, pp. 107-133, 1932. [Observations and formation of anchor-ice in Svir River and in Lake Ladoga leading to conclusion that it may be formed in absolutely stagnant waters and even under cover of surface-ice; anchor-ice formed in water having positive temperatures, while materials of river bed had negative temperatures; conditions favorable and unfavorable for formation of anchor-ice; in Russian, with brief abstract in English.]

(3) Glaciers--

The Ice-Age of the Earth, Tycos, April 1933, p. 77.

Fritiof Fryxell, The formation of glacier tables, J. Geol., v. 41, pp. 642-646, 1933.

Werner Heybrock, A note on the Aneto Glacier of the Maladetta Massif, Spanish Pyrenees, Geog. J., v. 82, pp. 260-263, 1933.

Douglas Johnson, Date of local glaciation in the White Mountains, Amer. J. Sci. (5), v. 25, pp. 399-405, 1933.

G. R. Spitular, Diluvial Ice-Age in equatorial regions, Bertr. Geophys., v. 38, p. 220, 1933.

W. B. Schostakowitsch, Über Altersbestimmung der Gletscher, Zs. Gletscherk., v. 21, pp. 139-145, 1933.

Ph. C. Visser, Benennung der Vergletscherungstypen, Zs. Gletscherk., v. 21, pp. 137-139, 1933.

Karl Wien, Zur Karte des Zemu-Gletschers, Zs. Gletscherk., v. 21, pp. 21-29, 1933.

Arctic

Gene A. Day, Solving the secrets of polar ice, Tycos, April 1933, p. 45.

Jean Louis Faure, Au Groenland, avec Charcot, Flammarion, Paris, 1933, 248 pp.

Johannes Georgi, Im Eis Vergraben, Erlebnisse auf Station Eismitte der letzten Grönland-Expedition Alfred Wegener, Münich, Paul Müller, 1933, 224 pp.

Johannes Georgi, Greenland as a switch for cyclones, Geog. J., v. 81, pp. 344-352, 1933.

Max Grotewahl, Grönland ohne Sensationen! Die Deutsche Polarstation, 1932-33, Ill. Ztg., Leipzig, Nr. 4635, pp. 38-39, January 11, 1934.

Herbert H. Kimball, Solar-radiation intensities in arctic regions, Beitr. Geophys., v. 32, Köppen- Band I, pp. 100-105, Leipzig, 1931.

Lauge Koch, The Danish three-year expedition to King Christian X Land, Geog. Rev., v. 23, pp. 599-607, 1933.

Fr. Loewe und K. Wegener, Die Schneepegelbeobachtungen (Wissenschaftliche Ergebnisse der Deutschen Grönland-Expedition Alfred Wegener, 1929 und 1930-31), Leipzig, 1933.

Donald B. MacMillan, Four years in the white north (with a foreword by Adolphus W. Greely), Hale, Cushman and Flint, Boston, 1933, 428 pp.

Ejnar Mikkelsen, The Blosseville Coast of East Greenland, Geog. J., v. 81, pp. 385-403, 1933.

Hans Poser, Ueber Abschmelzformen auf dem Ostgrönländischen Packeise und Landeise, Zs. Gletscherk., v. 21, pp. 1-20, 1933.

Knud Rasmussen, Explorations in Southeastern Greenland--Preliminary report of the sixth and seventh Thule expeditions, Geog. Rev., v. 23, pp. 385-393, 1933.

J. M. Scott, The land that God gave Cain--An account of the H. G. Watkins Expedition to Labrador, 1928-1929, Chatto and Windus, London, 1933, 281 pp.

Ernst Sorge, Mit Flugzeug, Faltboot, und Filmkamera in den Eisfjorden Grönlands, Drei Marken Verlag, Berlin, 1933, 208 pp.

Ernst Sorge, The scientific results of the Wegener Expedition to Greenland, Geog. J., v. 81, pp. 333-344, 1933.

H. U. Sverdrup, Als Meeresforscher mit dem Unterseeboot "Nautilus" im Nordpolargebiet, Polarbuch, Mittler, Berlin, 1933, pp. 1-22.

H. U. Sverdrup, Diurnal variation of temperature at polar stations in the spring, Beitr. Geophys., v. 32, Köppen- Band I, pp. 1-14, Leipzig, 1931.

L. R. Wager, The form and age of the Greenland Ice-Cap, Geol. Mag., v. 70, pp. 145-155, 1933.

Kurt Wegener, Die Deutsche Grönland-Expedition Alfred Wegener, Polarbuch, Mittler, Berlin, 1933, pp. 23-32.

"Alfred Wegeners letzte Grönlandfahrt.", Brockhaus, Leipzig, 1933.

Arctic--Continued

Ludwig Weichmann, Die Polarfahrt des Graf Zeppelin im July, 1931, Polarbuch, Mittler, Berlin, 1933, pp. 85-104.

Maurice Zimmermann, Etats Scandinaves, Régions Polaires Boréales, Géographie Universelle, Edited by P. Vidal de la Blanche and L. Gallois, v. 3, Colin, Paris, 1933, 310 pp.

J. Keränen, Über die Temperaturverhältnisse in Finnland Während der Vegetationszeit an den Nordgrenzen der Wichtigsten Kulturpflanzen (Ger.), Beitr. Geophys., v. 33, Köppen- Band II, pp. 261-267, Leipzig, 1931.

Hans W. Ahlmann, Scientific results of the Swedish-Norwegian Arctic Expedition in the summer of 1931, Vol. 1, Introduction and parts I-X. [Reprinted from Geografiska Annaler 1933; additionally valuable because of a bibliography of 55 titles on climate, snow, glaciers (in general, and the Arctic, in particular).]

Antarctic

R. E. Byrd, The flight to Marie Byrd Land, with a description of the map by Commander Harold E. Saunders, Geog. Rev., v. 23, pp. 177-209, 1933.

Ivar Hamre, The Japanese South Polar Expedition of 1911-1912--A little known episode of polar exploration, Geog. J., v. 82, pp. 411-423, 1933.

J. M. Wordie and Stanley Kemp, Observations on certain antarctic icebergs, Geog. J., v. 81, pp. 428-434, 1933.

Appendix

Appended to this report are the following papers which have been placed on file with the Secretary of the Section of Hydrology:

(1) Snow-surveying--Its principles and possibilities, by J. E. Church; reprinted from the Geographical Review of October 1933.

(2) Seasonal snow-survey and forecast of stream-flow, Nevada Cooperative Snow-Surveys, Humboldt Quadrangle, by Carl Elges, Forecaster, and J. E. Church, Adviser.

(3) Progress-report of the Cooperative Humboldt Forecast Committee, March 10, 1934, by J. E. Church.

(4) Snow-surveying and the Boulder Canyon Dam, reprint of radio broadcast, March 30, 1934, over Western Division of the National Broadcasting Company.

The Proceedings of the Western Interstate Snow-Survey Conference, now being printed by the Nevada Agricultural Experiment Station, will be distributed during 1934.

As promised in the last report, a complete list of all publications for each year will, so far as possible, be obtained and a collection made for purposes of loan.

Appreciation

The Chairman desires to mention again the generosity of the Nevada Agricultural Experiment Station which was not only the parent of western snow-surveying but has acted as patron both of the American Committee on Snow and the International Comission of Snow. Without its cooperation and financial support, many of the activities of the Committee would have been impossible.

The Committee also has been greatly aided by Emily Richards, who has acted as Secretary and assumed responsibility for the Questionnaire.

Recommendation

Approval is asked for the invitation to attend the International Congress of Ice at Helsingfors in 1936, and the request is hereby made that the Section of Hydrology appoint representatives and arrange other details of cooperation. [This was approved by the Union, April 27, 1934, following the Section's favorable recommendation.]

Nevada Agricultural Experiment Station,
Reno, Nevada

REPORT OF THE COMMITTEE ON GLACIERS, 1933-34

François E. Matthes, Chairman

The members of the Committee on Glaciers, 1933-34, are:

François E. Matthes, Chairman--United States Geological Survey, Washington, D. C.
Stephen R. Capps--United States Geological Survey, Washington, D. C.
Wm. B. Osgood Field, Jr.--Highlawn, Lenox, Massachusetts.
Wm. H. Hobbs--University of Michigan, Ann Arbor, Michigan.
Oliver Kehrlein--Sierra Club, 1050 Mills Tower, San Francisco, California.
Lawrence Martin--Library of Congress, Washington, D. C.
G. L. Parker--United States Geological Survey, 406 Federal Building, Tacoma, Washington.
Harry Fielding Reid--608 Cathedral Street, Baltimore, Maryland.
Carl P. Richards--The Mazamas, 306 Yamhill Street, Portland, Oregon.
R. H. Sargent--United States Geological Survey, Washington, D. C.
Earl A. Trager--National Park Service, Washington, D. C.

In its last report (Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 345-350) the Committee on Glaciers presented in tabular form the data concerning the variations in length of American glaciers--in the continental United States and Alaska--which it had gathered up to 1933, beginning with the earliest definite facts on record. Because of the comprehensive nature of that report it was impossible in the space available to discuss the records of individual glaciers or the causes and implications of their oscillations. But in the present report, which deals largely with the results of a single year (1933), there is opportunity to give something more than tabulated statistics, and accordingly the Committee presents for each glacier a brief note regarding its status and the changes it has suffered during the last two or three years. Pertinent meteorologic data are added wherever such data are at hand.

In thus giving its report for 1933 a more readable form the Committee is mindful of the fact that the oscillations of glaciers, and the variations in climatic conditions which they reflect, are subjects of popular as well as scientific interest; also, that the Committee is indebted for its annual budget of data largely to volunteer observers most of whom are not scientists. Its future reports will in large measure be patterned after this one.

Among its regular collaborators the Committee on Glaciers counts the park naturalists of Mount Rainier, Yosemite, Glacier, and Rocky Mountain national parks; the Superintendent of Mount McKinley National Park, Alaska; the Research Committee of the Mazamas, of Portland, Oregon; and the Committee on Glaciers of the Sierra Club. The last-named group, with which several members of the American Alpine Club are identified, has sprung into action during the past year, taking upon itself the task of studying the glaciers on Mount Shasta and also those ice-bodies in the Sierra Nevada that lie beyond the sphere of action of the park naturalist of Yosemite National Park. As a result plans are now laid for systematic observations on a number of important glaciers situated at intervals along the Cascade Range and the Sierra Nevada--that is, through a range of nearly 20° of latitude.

For data on the glaciers of Alaska the Committee depends largely upon observations and photographs by expeditions that visit the coast or the interior of Alaska for various scientific purposes. For detailed information and excellent photographs of several glaciers, however, the Committee is indebted to members of the Forest Service, the United States Geological Survey, the United States Coast and Geodetic Survey, and the National Park Service.

The Committee has the satisfaction to report that its affiliation with the "Commission Glaciologique" of the International Union of Geodesy and Geophysics was formally arranged during the past year. A special rescript of its reports, in which all measurements are stated in metric units, is transmitted annually to the Secretary of the Commission Glaciologique for use in the compilations of that international agency. The American Committee is now represented on the Commission Glaciologique by two of its members--Professor Wm. H. Hobbs, who is Vice-President, and by François E. Matthes, who is titular member representing the United States.

The Committee submits the following report on the advance and recession of glaciers in the United States and Alaska.

Glaciers of Mount Rainier

The following data are taken from an elaborate, illustrated report received from Park Naturalist C. Frank Brockman:

Nisqually Glacier, on the south side of Mount Rainier, continued to recede as in previous years. The steadiness of its recession is evident from the record of the last three years, namely: 1930-31, 49 feet; 1931-32, 50 feet; 1932-33, 44 feet.

The entire record for this Glacier, which was the first in the United States to be measured systematically, was published in the report of the Committee on Glaciers for 1932-33. The total recession measured by the National Park Service since 1918 is now 926 feet. The recession from 1857 to 1918, determined from reliable historic records, totals 2210 feet. The grand total since 1857, the year of the discovery of the Glacier by Lieutenant Kautz, is therefore 3136 feet.

In addition to the foregoing data from the National Park Service there has been received, through the courtesy of the Department of Public Utilities of the City of Tacoma, Washington, a copy of a contour-map of the lower Nisqually Glacier, drawn with 20-foot intervals on a scale of 400 feet to the inch. This map was made by the Department in October 1931, with the cooperation of members of the Water Resources Branch of the United States Geological Survey, the Bureau of Public Roads, and the National Park Service. The plane-table survey was executed by Bartlett G. Long, of the Bureau of Public Roads. It is intended to serve as a basis of comparison with a resurvey to be made in 1936, for the purpose of determining the shrinkage in volume of the glacier during the five-year period. As the Nisqually River is the source of hydroelectric power for the city of Tacoma, it was deemed important to make these detailed surveys in order that accurate estimates might be made of the rate of diminution of the ice-mass.

Emmons Glacier, the longest glacier in the United States, south of Alaska, is on the northeast side of Mount Rainier and is alimented in large part by the névé fields on the summit. Its length in 1933 was about 5.9 miles. Measurements of its recession were begun in 1930 and are as follows: 1930-31, 142.0 feet; 1931-32, 2.5 feet; 1932-33, 48.5 feet.

The vast quantities of rock débris that encumber the broad terminus of the Emmons Glacier render accurate determination of its recession difficult. The policy was adopted by Mr. Brockman of measuring from his base-line to the point where the stream issues from the clear ice. In 1931 that point was in a horseshoe-shaped reentrant flanked by two projecting tongues of débris-covered ice. In 1932 these tongues had melted away, leaving a fairly straight front. The recession of the ice-front as a whole probably varies less from year to year than the figures would seem to indicate.

Carbon Glacier heads in a large cirque on the north side of the peak but is in part alimented by avalanches from the summit névés. The reference-points for measurement of its recession were destroyed accidently in 1930 and again in 1931. The record consequently is confined to the period of 1932-33. The recession for that period was 12 feet.

South Tahoma Glacier lies on the southwest side of the peak and at its lower end is confluent with a branch of the Tahoma Glacier below the rock mass known as Glacier Island. If the two glaciers continue to recede as rapidly as they do at the present time, it will be not many years before they are separated from each other. The South Tahoma Glacier was first measured in 1931. The measured recession during 1931-32 was 37 feet and during 1932-33 was 13 feet.

Paradise Glacier is situated on the southeast side of Mount Rainier and is a relatively small ice-body that has no connection with the summit névés and originates wholly at altitudes below 9,000 feet. It was measured for the first time in 1932. The recession in 1933 was about seven feet.

Glaciers of Mount Hood

For several years past the Research Committee of the Mazamas, of Portland, Oregon, has measured the variations in length of three of the glaciers on Mount Hood--the

Eliot, Coe, and Ladd glaciers. Unfortunately stormy weather interfered with the completion of the measurements on September 23, 1933, but Carl P. Richards, the Chairman of the Committee, and his assistants managed nevertheless to determine the positions of the Eliot Glacier, which for the first time shows an appreciable advance. The records for these glaciers during 1931-33 are given in Table 1.

Table 1--Records for glaciers on Mount Hood, 1931-33

Glacier	1931-32	1932-33
Eliot	No change	Advance 25 feet
Coe	Recession 19 feet	
Ladd	No change	No record

Glaciers of Mount Shasta

A preliminary survey of the glaciers of Mount Shasta was made by Oliver Kehrlein, Chairman of the Committee on Glaciers of the Sierra Club, on September 22-24, 1933. A sketch-map showing the positions and outlines of the glaciers and a number of photographs were received from him. The glaciers covered are the Wintun, Hotlum, Bolum, Whitney, Konwakiton, Mud Creek, and Clear Creek glaciers. No measurements were made, but the report rendered contains the first substantial data on these ice-bodies since they were mapped by the United States Geological Survey in 1882-83.

Of particular interest are the data on the small Mud Creek Glacier, which does not appear on any of the topographic maps, yet which gave rise to the sensational and devastating mud-flows of 1924. Comparison of photographs taken in 1924 and 1933 shows that this Glacier has receded no less than 1300 feet during that interval. This rapid recession is explained in large measure by the headward erosion of the Canyon of Mud Creek and the consequent undercutting of the Glacier's terminus. Slides are of frequent occurrence in the poorly consolidated volcanic ash in which the Canyon is cut. These slides form temporary dams that impound the water and then break under its pressure. It was the repeated occurrence of this spasmodic action, promoted by rapid melting of the ice during unusually warm weather, that caused the disastrous mud-flows of 1924.

Glaciers of the Sierra Nevada

Park Naturalist C. A. Harwell, of Yosemite National Park, submits the following data on the Lyell, Maclure, Dana, and Conness glaciers. In October 1933, these glaciers were all found stripped of snow, save for a narrow zone in the vicinity of the bergschrund. This condition seemed remarkable in view of the fact that the snow-precipitation during the preceding winter had been unusually heavy and that the glaciers were still largely blanketed with snow in October 1932, when the heavy precipitation began. The explanation of their depletion in the autumn of 1933 is found in unusually strong ablation during long periods of clear, sunny weather in the summer months. This is an instance where a single warm summer more than offset two successive snowy winters.

The precipitation-data of Table 2 are from the floor of the Yosemite Valley, which lies 14 miles to the southwest of Mount Lyell and at an altitude of 3960 feet, or 7500 to 8000 feet below the general level of the glaciers.

Table 2--Precipitation-data, floor of Yosemite Valley, 1928-33

Year	Snowfall	Water-content
	inches	inches
1928-29	91	26.65
1929-30	74	26.81
1930-31	11.25	20.43
1931-32	168	25.66
1932-33	175	40.14

East Lyell Glacier on October 4 showed a recession of 18 feet. The stripping away of the snow revealed that the advance of 65 feet reported in 1932 was more apparent than real, the terminus having been built out by large masses of snow. The most reliable measurement in 1932 showed a recession of two feet, and the record for that year should be corrected accordingly.

Of unusual interest was the discovery on October 4, 1933, on the lower part of the East Lyell Glacier, about 30 feet above the moraine, of the carcass of a mountain sheep (Ovis canadensis sierrae), a species that is now almost extinct and has not been observed in the Yosemite National Park for some 50 years, although a few specimens still roam the southern part of the Sierra Nevada (M. E. Beatty, Mountain-sheep found in Lyell Glacier, Yosemite Nature Notes, v. 12, pp. 110-112, 1933). The body was in a mummified condition and complete save for the shells of the great horns and part of one leg, which were found, after some search, a short distance away. There was no indication of gnawing by coyotes. The presence on the rump of a patch of "leichenwachs" or corps-wax, according to Prof. Eric Wasmund, of Kiel University, Germany, who examined it, marks the initial stage in the formation of petroleum and indicates prolonged burial under pressure. It may be presumed, therefore, that the mountain-sheep has been entombed in the Glacier for a considerable period of years.

Speculation as to the length of that period induced Assistant Park Naturalist M. E. Beatty and Ranger Naturalist A. E. Borell, on October 20, 1933, to return to the Glacier in order to make some preliminary measurements of the rate of forward movement of the ice. The maximum movement in four days they found to be one inch, or an average of one-fourth of an inch per day. Assuming the mountain-sheep to have come to its death by falling into the bergschrund, which is situated 1936 feet above the point at which the carcass was found, they estimated that it might have been in transit within the ice-mass for some 240 years. It is realized, of course, that this figure must be excessive, as the rate of movement of the ice in October is near the minimum for the year. Further measurements will be made next summer in order to ascertain the maximum rate and to obtain a better basis for a computation of the length of time that the mountain sheep has lain entombed in the glacier.

West Lyell Glacier--The most reliable measurement on October 4, 1933, indicated a recession of seven feet. The advance of 15 feet reported in 1932 should be corrected to six feet.

Maclure Glacier on October 5, 1933, appeared to have receded 22 feet. However, as the terminus was deeply covered with snow in the autumn of 1932, the apparent advance of 52 feet then reported included in all probability a large amount of snow. The melting away of 22 feet of this snow in 1933 brings the front back to a position still 30 feet in advance of the position in 1931.

Dana Glacier--Measurements were made on October 6, 1933, to all the lobes of this irregular ice-body. The most trustworthy indicate an apparent recession of 30 feet. An apparent advance of 31 feet was noted at this point in 1932, but this advance, as in the case of the Maclure Glacier, probably included considerable snow. The apparent advance of 40 feet at another point, reported in 1932, is to be questioned for the same reason.

Conness Glacier--The east lobe of this Glacier was found to have shrunk back 177 feet from the position noted in 1932; but in this case, too, the advanced position of 1932 must have been more apparent than real, owing to heavy masses of snow that extended beyond the Glacier's terminus.

The following glaciers to the south of Yosemite National Park were visited in 1933 for the first time at the instance of the Committee on Glaciers. The observations were made by Oliver Kehrlein, the Chairman of the Committee on Glaciers of the Sierra Club.

Minaret Glacier--This Glacieret is so situated that no base-line can be laid out across its front, but good photographs were taken showing its present form and extent. The two lobes overlook a steeply inclined cliff and cannot advance without the ice breaking off in avalanches. The Minaret Glacier therefore can at present register only recession. Comparison with a photograph taken by Ansel E. Adams in 1923 shows that the ice-mass has suffered but little change in the interim. If anything, it has gained slightly in volume.

Darwin Glacier--A photograph of this Glacieret was taken by Mr. Kehrlein from the mountain above it. The ice-body is walled in by a massive terminal moraine and like many other glaciers in the Sierra Nevada appears to have had approximately the same size for a considerable period. It still extends out to the moraine, but its surface now lies well below the level of the moraine crest--about ten feet, perhaps, to judge from the photograph.

North Palisade Glacier--This, the southernmost of the larger glaciers of the Sierra Nevada, situated in latitude 37° 06', was visited by Mr. Kehrlein on August 13, 1933. A preliminary base-line was laid out tangent to the most advanced lobe, and photographs were taken showing the Glacier from different angles. These together with the excellent photographs that were taken by Francis P. Farquhar in 1931 cover the Glacier very completely.

The North Palisade Glacier also is walled in by a massive frontal moraine. Its surface in 1933 was about seven feet below the top of this moraine and appeared to have sunk several feet since it was observed in September 1928. This fact was confirmed by Messrs. H. W. Mendenhall and R. Brackett of Big Pine, California, who have visited the Glacier from year to year.

Table 3 gives the data on snow-precipitation from the regular snow-survey courses nearest to the North Palisade Glacier.

Table 3--Snow-precipitation near North Palisade Glacier, 1932-33

Locality	Depth of snow		Water-content		Computed percentage of normal water-content	
	1932	1933	1932	1933	1932	1933
Bishop Pass (altitude 11,400 ft)	92.4	68.9	40.2	24.9	...	..
Big Pine No. 1	92.3	59.5	35.4	17.2	157	76
Big Pine No. 2	74.4	42.6	27.7	12.6	190	86
George Lake	75.3	35.7	30.8	12.3	...	..
Sawmill	74.4	41.0	28.2	12.3	136	64

Glaciers of the Rocky Mountains

In Glacier National Park, Montana, three of the more important glaciers, the Grinnell, Blackfoot, and Sperry, were visited by Park Naturalist G. C. Ruhle. His report is as follows:

Grinnell Glacier on September 14, 1933, had neither advanced nor receded. The foremost part of the ice-front rested against a low rock step.

Blackfoot Glacier--The main lobe on September 4, 1933, appeared to be 64 feet in advance of last year's position. (This measurement probably includes considerable new snow burying the real ice-front.)

Sperry Glacier, after marked recession during the period 1929 to 1931, is again advancing. Measurements in 1932 showed an advance of 18 feet. During 1933 the advance was so great as to sweep away the markers set in 1931. On September 7, 1933, Mr. Ruhle reports, the maximum advance appeared to be of the order of 500 feet. It seems probable, however, that not the ice-body itself but the heavy snow-cover that buries it since the previous winter extends so far out beyond the position of 1932.

In Rocky Mountain National Park, Colorado, two cirque glaciers, the Tyndall and the Andrews, were measured by Park Naturalist Dorr G. Yeager. The Tyndall Glacier had receded nearly 33 feet and the Andrews Glacier 9.5 feet since the previous year. The snowfall during the winter of 1932-33, Mr. Yeager reports, was the lightest that has been measured at Estes Park in ten years.

Glaciers of Alaska

Paul C. Whitney, of the United States Coast and Geodetic Survey, reports the following concerning the McCarty Glacier (The recent retreat of McCarty Glacier, Alaska, Geog. Rev., v. 22, No. 3, pp. 389-391, 1932).

McCarty Glacier, one of the many glaciers that drain the vast ice-field on the Kenai Peninsula, reaches sea-level at the upper end of East Arm, Nuka Bay. Surveys of this bay by the United States Coast and Geodetic Survey in 1925 and 1927 show that this Glacier receded fully one mile during those two years. Comparison of the survey of 1927 with a reconnaissance-map made by the United States Geological Survey in 1909, furthermore, shows that the Glacier receded a total distance of 1.9 miles during that period. Its recession is thus proceeding with increasing rapidity. A great terminal moraine that stretches across East Arm a short distance below the Glacier's position of 1909, and that rises from a depth of 100 fathoms to somewhat above mean lower low-water, gives evidence of a prolonged halt of the Glacier during the years preceding 1909.

From Harry J. Liek, Superintendent of Mount McKinley National Park, word was received that base-lines were laid out in September 1933 at the fronts of the Thorofare, Toklat, and East Fork glaciers. Photographs were transmitted by him showing the positions of the termini of these glaciers. Observations on the great Muldrow Glacier have been discontinued, the lower portion of that Glacier being largely stagnant and so heavily covered with débris that the boundaries between the ice-mass and the surrounding moraines are not recognizable.

The following data were received from Dr. Chester K. Wentworth and Louis L. Ray, of Washington University, St. Louis, who in 1931 made a glaciological expedition through the Juneau, Copper River, Valdez, and Seward districts of Alaska. The positions of the ice-fronts were determined by them phototopographically and then compared with the positions shown on previous maps.

Mendenhall Glacier has receded since 1909 an average distance of 1280 feet. The maximum recession since 1906, measured along the southeastern drainage stream, is 3375 feet, or an average of 135 feet per year.

Herbert Glacier, which lies only a few miles to the south of the Mendenhall, appears to have receded at a similar rate. The front of this Glacier has not yet been plotted, but the photographs show a recession comparable to that of the Mendenhall.

Norris Glacier was not mapped, but evidences of its recent recession are manifest. The southern lateral margin has receded at least 400 feet since the invasion of the spruce forest, and the frontal lobe is considerably lower than it was at that time.

Taku Glacier, in contrast to the other glaciers observed, has made a conspicuous advance. The maximum advance since 1909 is 7600 feet, that is, an average of 304 feet per year. In the two years since the aeroplane-survey by the Forest Service in 1929, a pronounced tongue, somewhat east of the center, has advanced 1650 feet. According to a report received January 27, 1934, from E. P. Pond, of Juneau, a further advance was noted in the fall of 1933. The exceptional advance of the narrow tongue appears to be due to the grounding of the western margin of the Taku on the submerged delta of the nearby Norris Glacier. The Taku's prodigious advance is as yet unexplained.

Allen Glacier, according to descriptions by Tarr and Martin, had in 1909 a typical expanded terminal bulb and was then already developing a crenulate margin due to irregular melting. By 1931 this process had made great inroads on the former arcuate margin.

Grinnell Glacier is bifurcated at its lower end by a central roche moutonnée in the steep valley-floor. Retreat of the active portion of the north tongue, from 1910 to 1931, is estimated at 800 feet, and that of the south tongue at 3000 feet. In the latter estimate the moraine-covered mass of stagnant ice that was left behind is considered as no longer part of the Glacier.

Miles Glacier, since 1910 has been cut back along its southern front of clear ice, facing Miles Lake, a distance of more than two-thirds of a mile. This great recession, which involves the loss of approximately three square miles of ice, is probably due largely to wave attack--Miles Lake, a ponded part of Copper River, now being greatly enlarged. Little areal change could be noted in the northern part of the Miles Glacier terminus, which is covered with débris and vegetation.

Childs Glacier--The portion fronting on Copper River appears to have receded considerably since 1910. A gravel-bar is now exposed along the entire ice-front, with the exception of a stretch of a few hundred feet that is covered by ice-falls. As a result the ice-front is now no longer subject to undercutting by the River at normal water-stages. The average recession from 1910 to 1931 is estimated at 500 feet. The northern tongue, which advanced so threateningly in 1910, has retreated about 650 feet. It is now a triangular mass of stagnant ice, melting in situ, and in places heavily covered with débris.

Valdez Glacier has receded considerably from identifiable landmarks shown on previous maps. The mean recession, from 1910 to 1931, is 1175 feet, the maximum being 1350 feet. An area of 162 acres has been vacated by the Glacier during that period.

Bear Lake Glacier appears to have receded slightly, but no dates or landmarks for comparison are available.

Trail Glacier likewise shows evidence of recent recession, but neither dates nor landmarks are available for comparison. Two photographs taken from the same point on the railroad, five miles distant, in 1911 and 1931, reveal no notable difference in the marginal outline.

Bartlett Glacier, according to railroad officials, occupied in 1906 a position possibly 500 feet in advance of its position in 1931. By 1911 it had receded approximately to the outline of 1931, but in 1916 it had again advanced close to its position of 1906. Since 1916 it has receded on an average about 20 feet per year.

Spencer Glacier, so far as known, has been in recession throughout the last two decades. Comparison of the map made by Wentworth and Ray in 1931 with that made by the United States Geological Survey in 1911 shows a recession averaging 1480 feet. The Placer River, which impinges against the south side of the Glacier, now cuts a much wider bay in the ice than formerly, and if it continues to cut, may in the near future take a new course to the northeast of the large roche moutonnée that is situated northwest of the gorge below Tunnel Station on the Alaska Railroad.

H. B. Washburn, Jr., upon the basis of observations between 1930 and 1933 (Science, N.S., v. 79, pp. 249-250, 1934), reports that four glaciers measured by him at Lituya Bay and Crillon Lake were advancing at the rate of two feet per week, while a fifth had receded at least 300 feet in the last three years. The South Crillon Glacier is at present advancing into a forest and has greater extent than it has had in fifty years.

The Nunatak Glacier in Yakutat Bay in 1933 had receded nearly five miles from the position determined by Tarr and Martin in 1909. The Hidden Glacier had receded at least two miles since that time, but the Turner, Haenke, and Hubbard glaciers appeared essentially unchanged.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, 1933-34

Charles H. Lee, Chairman

The members of the Permanent Research Committee on Absorption and Transpiration are:

Charles H. Lee, Chairman--58 Sutter Street, San Francisco, California.
Harry F. Blaney--600 Federal Building, Los Angeles, California.
Lynn Crandall--United States Geological Survey, Idaho Falls, Idaho.
S. T. Harding--12 Engineering Building, Berkeley, California.
Charles R. Hursh--Appalachian Forest Experiment Station, Asheville, North Carolina.
Burton E. Livingston--Johns Hopkins University, Baltimore, Maryland.
W. C. Lowdermilk--Soil Erosion Service, Department of the Interior, Washington, D. C.
G. E. P. Smith--University of Arizona, Tucson, Arizona.
J. E. Weaver--University of Nebraska, Lincoln, Nebraska
W. N. White--United States Geological Survey, Washington, D. C.

The one definite accomplishment of the Committee during the past year has been the completion of a tentative list of definitions of terms pertaining to absorption and transpiration. The preparation of this list was commenced soon after the organization of the Committee, and it represents the results of several years work in which all members of the Committee participated. In view of the fact that it has not been reviewed in its final form by all members of the Committee, the list is presented tentatively in attached Appendix A, subject to modification after further comments have been received. Discussion by those who are not members of the Committee will be especially welcome. The tentative list of definitions is presented as a part of the Committee's report.

The Committee has endeavored to keep in touch with all current work on absorption and transpiration in the United States since its last report, and submits the following partial statement of research projects.

Research in absorption of rainfall and transpiration by the California Forest Experiment Station

Researches were continued in factors affecting absorption of rainfall and transpiration in the program of forest influences of the California Forest Experiment Station. New installations included a major watershed-study known as the San Dimas Experimental Forest in Southern California. The object of this study is to determine the rôle of chaparral forest vegetation in the maximum beneficial yield of water from mountain-watersheds. It is planned to proceed with experimentation from small runoff-plots through small drainage-areas to entire watershed. The flood-control dams of the Los Angeles County Flood-Control District will serve as outside controls for the two drainages included within the experimental forest. During the past year two sets of triplicate watershed-installations were completed. One set of triplicate watersheds has an average elevation of 2500 feet, and the second 5000 feet. The area of these experimental watersheds varies from 50 to 100 acres, and represents as uniform a condition as could be found. Each watershed is equipped with a duplicate water-measuring device and with an Ambursen type dam to impound runoff-water and sediments. Rainfall in the watersheds is measured by a close network of standard and automatic rain-gages. Experimental procedure has new features. All the watersheds will be run with the mantle of vegetation undisturbed for the first stage of the experiment, which will be less than five years. At the beginning of the second stage two watersheds of each triplicate set will be burned clean. The vegetation on one of each set will be permitted to return naturally. Vegetation on the other burned watershed of each set will be burned annually to maintain the surface in as barren a condition as possible. The second stage will last for five years or longer. The procedure for experimentation in the third stage will be determined at the end of the second stage. Preparations are being made to measure the runoff from intermediate-size watersheds of approximately 1000 acres.

Detailed studies in transpiration of chaparral species and forest trees are being prepared for in the construction of large lysimeters. Details of these installations will be included in the next year's report. Most of the above work was initiated under the direction of Dr. W. C. Lowdermilk, Vice-Director, Soil Erosion Service, United States Department of the Interior, Washington, D. C.

Research on stream-flow and erosion by the Appalachian Experiment Station

The major purpose of the stream-flow and erosion project is to determine the comparative efficiency of different types of vegetative cover for watershed-protection in the Southern Appalachian Region. This purpose is being carried out through two closely related lines of investigation. The first involves plot studies of the comparative efficiency of certain types of vegetative cover (or its absence as in the case of eroding fields) in influencing absorption and percolation and in protecting the soil from erosion. A second line of investigation is an extensive study of the organic layers of the soil-profile (humus-type) as influenced by the vegetation-type, coupled with an examination of the effectiveness of different humus-types in governing absorption and percolation of precipitation and in protecting the soil from erosion.

Beginning with July 1, 1932, continuous records have been made of the amount of storm-flow following each storm from ten permanent plots on the Bent Creek Forest. From these plots, representing five common cover-types, storm-flow was measured as surface-runoff and also as sub-surface flow at 12 inches. These continuous records are the first of their kind ever obtained in the Southern Appalachian Mountains. These records and others will serve as a basis for interpreting the movement of storm-flow from representative cover-types within the region.

The usefulness of the records will increase with the continuation of observation. Sixty-six rain-storms and two snow-storms occurred during the 12-month period ending June 30, 1933. The work is being carried on under the direction of Dr. C. R. Hursh, Forest Ecologist, Appalachian Forest Experiment Station, United States Forest Service, Asheville, North Carolina.

Research-projects conducted in the southwest during the past year by the Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture

(a) Water requirements of citrus trees--(1) General studies on the use of water by oranges and lemons in Southern California. Special studies at San Dimas on transpiration-use by lemon trees. This work is being conducted by Harry F. Blaney and C. A. Taylor. (2) Consumptive use of water by grapefruit trees at Phoenix, Arizona, by Karl Harris.

(b) Studies on hourly rates of transpiration at Pomona, California, C. A. Taylor--Sunflowers and small citrus trees are used. The relation between moisture-equivalent and wilting-coefficient is being studied for various soil-types.

(c) Consumptive use of water by field crops--This work is being conducted on the Yuma Experiment Farm, Bard, California, by Harry F. Blaney and Dean Bloodgood in cooperation with the Bureau of Plant Industry.

(d) Transpiration and evaporation along stream-channels--Measurements are being made of evapo-transpiration losses by canyon-bottom vegetation in Devil Canyon, near San Bernardino, California. This is a cooperative investigation, being conducted by Harry F. Blaney of the Bureau of Agricultural Engineering and C. J. Kraebel of the California Forest Experiment Station.

(e) Water spreading--Experiments on the recharge of ground-water by spreading of surplus stream-flow by A. T. Mitchelson. Several stations have been established in California, and ditches, basins, and shafts are being used.

Research-work in Nebraska

The following studies and reports on water-usage are reported as being in progress in Nebraska by Dr. J. E. Weaver, Professor of Plant Ecology, University of Nebraska, Lincoln, Nebraska.

Studies on competition in sudan grass, Fernando de Peralta. [Includes water-usage of this forage-plant.] (In press.)

Growth, structure, and interrelationships of three types of low prairie, V. Hougen. [Includes studies on water-table and water-usage.]

Comparison of the environment and some physiological responses of prairie vegetation and cultivated corn, Evan Flory. [Includes water-usage in cornfield and prairie.] (In press.)

Comparison of the environment and some physiological responses of prairie vegetation and wheat, Wm. Noll. [Includes water-usage in wheat-field and prairie.]

Relation of roots to the organic matter in the soil-profile, J. E. Weaver, V. Hougen, and M. D. Weldon. (In press.)

Studies on erosion in native grassland, pastures, and cultivated fields, J. E. Weaver and Wm. Noll.

Reports on consumptive use in California

Two important reports presenting the results of research work in California on large-scale consumptive use of agricultural crops and natural vegetation have been published during the past year.

Water losses under natural conditions from wet areas in Southern California (Bull. No. 44, Div. Water Resources, State of California, 1934)--This report gives basic data which may be applied in evaluating water now wasted that might be put to profitable uses. This report contains 176 pages, including 74 tables and 42 plates, and is divided into two parts.

Part I, Consumptive use of water by native plants growing in moist areas in Southern California, by Harry F. Blaney--This is a report by the Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, dealing with the disposal of water by transpiration and evaporation in various parts of Southern California. It presents the results of research-studies on consumptive use of water by various types of native water-loving vegetation, commonly found along stream-beds, swamps, and cienagas, and evaporation from moist soils without vegetative growth and evaporation from free water-surfaces. The vegetation includes tules, willows, wire rush, salt grass, and bermuda grass on the valley floors. A large-scale experiment is reported on the evapo-transpiration losses by canyon-bottom vegetation, such as Alder, Sycamore, Bay, Willow, and Maple trees.

Part II, Ground-water supply and natural losses in the Valley of Santa Ana River between Riverside Narrows and the Orange County Line, by Harold C. Troxell--This is a report of investigations made by the Water Resources Branch, Geological Survey, United States Department of the Interior, dealing with loss of water from Santa Ana River in the lower Santa Ana Canyon, together with an estimate of inflow from ground-water above Lower Santa Ana Canyon.

Report on State Water-Plan, San Joaquin River Basin, by Edward Hyatt, State Engineer (Bull. No. 29, Div. Water Resources, State of California, 1934)--This report presents an application of Harding's method (Trans. Amer. Soc. C. E., v. 94, p. 1368, 1930) of computing consumptive use from mixed agricultural crops covering large areas based upon total annual inflow of surface-water into the area, acreage irrigated, and annual change in ground-water level based upon numerous systematically observed water-levels in wells. With records available for nearly ten years in a number of large valley-areas, it was found possible to graphically analyze the data and by a simple method to determine the annual consumptive use from these areas. The results obtained for different areas were very consistent and indicated reasonable accuracy of results. Rainfall is too small in this region to represent an increment to ground-water and surface-water entering the various areas during the period of study was practically all consumed locally. The report is a notable instance of the practical study and application of hydrologic data in solving important engineering problems.

Other instances of the practical application of ground-water and consumptive-use data have been in the study of relations of supply and pumping-draft from wells in various California valleys, as a basis for determining conditions under which farm loans by the Federal Land Bank might be justified. Reports incorporating such studies in different areas were prepared by both S. T. Harding, M. Amer. Soc. C. E. of Berkeley, California, and Charles H. Lee, M. Amer. Soc. C. E., San Francisco, California.

Future work

During the coming year it is hoped that the report on transpiration, an outline for which accompanied the 1933 report of the Committee, may be completed. The bibliographies pertaining to absorption and transpiration will also receive attention.

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APPENDIX A--TENTATIVE STATEMENT OF TERMS WITH DEFINITIONS

Introduction

The purpose of this list of definitions is to formulate in concise terms the basic ideas pertaining to the subject-matter of the Committee's activities. It is hoped that it will serve to facilitate the exchange of ideas among hydrologists and encourage utilization of the results of research in other related fields, and particularly that in foreign countries. It is believed that recent research-work in the physics and chemistry of liquid surfaces is an especially fruitful field for study in connection with the movement of soil-moisture in unsaturated materials.

Definitions standardized by previous usage have been followed as far as possible. The processes involved in absorption have received so little analytical study, however, that it seemed desirable to make more specific the meaning of certain loosely-defined terms in general use, and to propose new terms for certain processes or conditions which frequently are not clearly recognized among hydrologists. The proposal of new terms has been undertaken only when it was felt by several members of the Committee that adequate terms were lacking. Where possible, definitions have been purposely stated so as to make a distinction between saturated and unsaturated materials.

The definitions as stated incorporate all suggestions which have been offered by members of the Committee, but the list does not include all terms which have been suggested. In addition to receiving the contributions of members, the published works of leading hydrologists and soil physicists have been freely consulted, particularly those of Meinzer, Meyer, Horton, and Viehmeyer. The results of research-work in the physics and chemistry of surfaces have also been reviewed, reference having been made especially to the works of Adam (The physics and chemistry of surfaces, N. K. Adam, Oxford University Press, 1930) and Rideal (An introduction to surface-chemistry, E. K. Rideal, Cambridge University Press, 1926).

For convenient reference the definitions have been arranged under certain headings. Those classified as "general" pertain principally to the solid material which forms the container or supporting framework for subsurface water. This heading also includes the definition for "precipitation", which is the ultimate source of all subsurface water. These definitions are all well known and need no comment.

Under the heading "subsurface water" are included definitions of the various zones and classes of subsurface water. The terms "pellicular water" and "mobile water" are new. Their introduction is occasioned by the fact that capillarity is, strictly speaking, a special case of the more general and more recently studied phenomena of surface-pressure of liquid surfaces. The phenomenon of capillarity, although produced by the pressure of curved liquid surfaces, pertains specifically to the rise of a liquid in small tubes immersed in the liquid. It is illustrated in nature by the capillary fringe above a water-table. On the other hand, water occupying films in the zone of aeration above the capillary fringe is beyond the influence of capillarity, being controlled partly by the forces of surface-pressure and gravity and partly by the molecular forces of adhesion. It is believed that the analysis of the behavior of soil-water above the capillary fringe can be made more clearly if divorced from association with the special phenomenon of capillarity. It is with this consideration that the new terms "pellicular water", referring to that held by the forces of molecular adhesion, and "mobile water", referring to that controlled by the forces of liquid surfaces and gravity, have been introduced. The term "capillary water" has been limited to mobile water within the capillary fringe instead of applying it generally to water anywhere within the zone of aeration.

The heading "movement of subsurface water" includes the three terms "film-flow", "percolation", and "cavern-flow", which are descriptive of flow-types; the terms "surface-tension" and "surface-pressure" are descriptive of forces which actuate film-flow; and the terms "permeability" and "impermeability" are terms which characterize solid materials with reference to the movement of subsurface water. "Film-flow" is a new term occasioned by the limitation of the term "capillary water" to the capillary fringe. Its purpose is to differentiate the flow through films in unsaturated material from that in saturated material. For the latter the term "percolation" is reserved. Interstitial sizes differ widely in natural materials, so that only a portion of them are saturated even in the capillary fringe. Movement within the capillary fringe may thus be considered as film-flow. The term "surface-pressure" and its mathematical equivalent "surface-tension" represent the forces which in conjunction with the force of gravity actuate film-flow. The definitions are drawn largely from Adam. The function of surface-pressure of films in the movement of suspended water has not been as generally recognized by hydrologists and engineers as is warranted by its importance. This is especially true with respect to the entry-head of surface-water discharging into unsaturated material and the movement of soil-moisture. Other definitions under this heading are standard.

"Soil-moisture" terms were introduced in the list of definitions because of their practical usefulness in agriculture and in the study of transpiration. The maximum moisture-content of the soil available for plant-growth includes a portion of the mobile water and a portion of the pellicular water. "Moisture-equivalent" is easily measured, and in many soils is representative of the maximum moisture of which a portion is available to plants. It includes the more slowly-moving portion of mobile water and the available portion of pellicular water. "Field-capacity" closely corresponds with "moisture-equivalent" in all but the sandier soils, in which it more accurately represents the maximum moisture of which a portion is available to plants than does moisture-equivalent. If carefully measured with ample time allowed for complete drainage, "specific retention" should closely represent pellicular water. "Permanent wilting-percentage" will usually represent a moisture-content less than pellicular water since a portion of the latter is available for plant use. The terms "ultimate wilting-point", "wilting-range", "available water", "readily available water", and "initial moisture-deficiency" were suggested by Messrs. Harry F. Blaney and C. A. Taylor. Some of these are already in use among soil investigators and others are new.

Under "absorption" is included its definition and that of the various processes by which absorption takes place. The terms "wetting" and "spreading" are defined in accordance with their accepted technical meaning and are included for the purpose of presenting all the essential steps by which water enters the ground. They are adapted largely from Adam. "Infiltration" is a term frequently used in a sense more or less synonymous with absorption but has been limited to liquid water. The limited aspect of the term has been retained in the definition, and it has been further limited to water entering the zone of aeration. Loss of water from streams into unsaturated material is included in infiltration. "Seepage" is limited to flow into or from saturated material following the definition given by Meinzer. The terms "rainfall-penetration" and "water-spreading" are in common use and their definitions generally accepted.

General

Atmosphere--The outer part of the Earth surrounding the lithosphere and hydrosphere, and consisting predominantly of air.

Hydrosphere--The liquid and solid water resting upon the lithosphere.

Lithosphere--That part of the Earth which is composed predominantly of rocks, including the products of rock-disintegration and other incoherent solid materials, together with everything within the rocky crust.

Earth--The softer materials of the lithosphere as distinguished from firm rock. Its basic constituents are the products of rock-disintegration and erosion, consisting of gravel, sand, silt, and clay, the latter in both particle and colloidal form. It may also be of organic, diatomaceous or volcanic origin.

Soil--The top layer of earth penetrated by roots and containing more or less organic matter.

Interstice--A space or void in rock or earth not occupied by solid matter. Interstices may be either interconnecting or isolated. Interconnected interstices occur as (1) openings between particles or grains in earth or rock, (2) fractures in rock, and (3) as large tubular or cavernous openings in soluble rocks and in lavas.

Capillary interstice--One small enough for water to be held by capillarity at an appreciable height above the hydrostatic pressure-level, and large enough to preclude molecular attraction of its walls from extending across the entire space. The movement of water in capillary interstices conforms to the laws of stream-line flow (percolation). Such water is partly pellicular and partly mobile.

Super-capillary interstice--One larger than a capillary interstice in which water is not held at an appreciable height above the hydrostatic pressure-level and through which the movement of water may be turbulent.

Sub-capillary interstice--One smaller than a capillary interstice in which molecular attraction of its walls extends to the entire space and water is held immovable against gravity by the forces of adhesion. Such water is essentially pellicular.

Porosity--The property of a rock or earth of containing interstices. It is quantitatively expressed as the percentage of the aggregate volume of interstitial space to total volume.

Apparent specific gravity (volume-weight)--The ratio of the weight of a unit volume of oven-dry soil of undisturbed structure to that of an equal volume of water under standard conditions.

Precipitation--The process by which water in liquid or solid state is discharged out of the atmosphere, principally upon a land- or water-surface. It is the process by which atmospheric water becomes surface- or subsurface-water. It includes dew, rain, hail, and snow. The term "precipitation" is also used to designate the quantity of water that is precipitated. Rate of precipitation is expressed in depth (measured as liquid water) precipitated upon a horizontal surface at specified location and elevation per unit of time--generally in inches or centimeters per day, month, or year.

Subsurface-water

Subsurface-water--Water that occurs in the lithosphere. It may be in liquid, solid, or gaseous state.

Zone of saturation--The zone of the lithosphere in which the interstices of permeable rock or earth are completely filled with water under hydrostatic pressure.

Zone of aeration--The zone of the lithosphere in which the interstices of permeable rock or earth are not (except temporarily) filled with water under hydrostatic pressure. The interstices contain either water and air, or if within the capillary fringe, may be filled with water that is held by capillarity.

Capillary fringe--The belt of subsurface-water overlying the zone of saturation in material having capillary interstices, some or all of which are filled with water that is continuous with the zone of saturation but held above that zone by capillary forces acting against gravity. Materials having only subcapillary interstices are impermeable and are not regarded as having a capillary fringe. In materials whose interstices are supercapillary, the capillary fringe is practically absent.

Suspended water--Subsurface-water partially occupying interstices in the zone of aeration. It may be classified as hygroscopic, pellicular, mobile, or capillary.

Hygroscopic water--Water adhering to the surface of solid particles or the walls of fractures which is in equilibrium with atmospheric vapor. It is essentially the water which molecular attraction can hold against evaporation.

Pellicular water--Suspended water held by molecular attraction in films adhering to the surface of solid particles or the walls of fractures. It is fixed water capable of partial extraction by root-absorption and evaporation but not moved appreciably by gravity nor the unbalanced film-forces resulting from evaporation and transpiration. (Term derived from the Latin word "pellis" meaning "skin"; proposed by Dr. C. F. Tolman, Department of Geology, Stanford University, California.)

Mobile water--Suspended water occupying films adhering to the surface of solid particles or to the walls of fractures, but in excess of pellicular water. It is free to move in any direction under the pull of the resultant of the force of gravity and unbalanced surface-pressure of films. It is frequently termed "gravity-water" or "free water."

Capillary water--Mobile water suspended in the capillary fringe above the water-table. It moves with the capillary fringe as the latter rises and falls with the fluctuations of the water-table. When the water-table is shallow it moves upward to replace loss by evaporation and transpiration as actuated by the resultant force of unbalanced surface-pressure of films minus the downward pull of gravity.

Ground-water--Subsurface-water occupying interstices in the zone of saturation. It may be classified as water of saturation, or that which completely fills the interstices of rock, or of earth whose particles are in contact, and as water of supersaturation, or that which is in excess of the water of saturation, in earths such as quicksand, plastic clay, or flowing mud, whose particles have lost contact and are more or less separated by water.

Water-table--The upper surface of a zone of saturation except where that surface is formed by an impermeable material.

Movement of subsurface-water

Surface-tension--The mathematical equivalent of the free surface-energy per unit area in the interface liquid-air due to the unbalanced inward pull or pressure exerted upon the layer of molecules composing the liquid surface. A hypothetical surface-tension is assumed for purposes of computation, and is assumed as acting parallel to the surface in all directions.

Surface-pressure--The inward pull exerted upon the layer of molecules composing the liquid surface of a liquid-air interface. Surface-pressure is sometimes termed "capillary pressure" or "negative hydraulic pressure." If the liquid surface be curved, the pressure is greater on the concave side than the convex by an amount which depends upon the surface-tension and the curvature. Capillarity results from this variation of surface-pressure with curvature of surface. The liquid surface in a small tube assumes a curved surface whose degree of curvature depends upon the liquid-solid contact-angle and the radius of the tube. The pressure upon the concave upper side of the liquid surface in the tube being greater than on the convex under side, the water rises in the tube, the height of the capillary rise representing the difference in surface-pressure inside and outside the tube. Similarly, local changes of the amount of water in a film-system in unsaturated earth by infiltration, transpiration, or evaporation, produce changes of concavity of the local film-surfaces, and unbalanced surface-pressure in the film-system. Under the influence of the latter, mobile water will travel by film-flow from points of greater to lesser abundance of water until equilibrium is reestablished. Flowing or sheet surface-water discharging into unsaturated material enters a system of films enclosed by curved liquid-air surfaces, and the hydraulic pressure-head is opposed by the surface-pressure of the film-system. The hydraulic head must be reduced by the surface-pressure of the film-system and possibly entry losses in order to obtain net entry head.

Film-flow--The movement of mobile suspended water in any direction through a system of interconnecting films adhering to the surface of solid particles or the walls of fractures in the zone of aeration. It is produced by the resultant of the force of gravity and unbalanced surface-pressure of films. The latter may result from local loss from films by evaporation and transpiration, from local addition to films by infiltration, or by fluctuation of the water-table. In this type of flow, loss of head due to friction varies directly as the velocity (Darcy's law). It has previously been variously termed "capillary migration", "capillary movement", etc.

Percolation--The movement of ground-water in stream-line flow in any direction through small interconnected and saturated interstices of rock or earth, principally of capillary size. It is produced by hydrostatic pressure due to the elevation (head of position) of the water-table in material which permits free movement in any direction, or to pressure-head under conditions of confinement (artesian pressure). It corresponds with flow in pipes of very small diameter or at very low velocities. In this type of flow, loss of head due to friction varies directly as the velocity (Darcy's law).

The term "percolating water", as used in a legal sense, is limited to diffused ground-water unconnected with a stream or other definite body of water, although it may be tributary to and ultimately reach such. Used in this sense it is distinguished from definitely known underground streams or the subflow of surface-streams. Following the broader hydrologic definitions, however, the latter might be termed either "percolation" or "cavern-flow", depending upon the size of interstices.

Cavern-flow--The movement of water in turbulent flow through large openings in rocks or coarse sorted granular material, produced either directly by gravity, when it corresponds with the flow of water in surface-streams, or by hydrostatic pressure, when it corresponds with the flow of water through pipes. In this type of flow, loss of head due to friction varies approximately as the square of the velocity.

Permeability--The property of a rock or earth which permits appreciable movement of subsurface-water through it either when unsaturated and actuated by the resultant force of gravity and surface pressure of films, or when saturated and actuated by hydrostatic pressure of the magnitude ordinarily encountered in natural subsurface-water. It is also termed "perviousness."

Impermeability--The property of a rock or earth which does not permit water to move through it perceptibly under the pressure ordinarily found in subsurface-water. It is also termed "imperviousness."

Certain highly-porous materials such as clays may be impermeable because the interstices are subcapillary in size. Bodies of impermeable material, such as impermeable clay, may lie within either the zone of saturation or the zone of aeration, but may not be an active functional part of either zone.

Soil-moisture

Moisture-equivalent--The amount retained by a soil in a standardized apparatus when the moisture-content is reduced by means of a constant centrifugal force (1000 times gravity) until brought into a state of capillary equilibrium with the applied force. It is expressed as per cent of dry weight.

Field-capacity--The amount of water retained in the soil after excess mobile water has drained away and the rate of downward movement has materially decreased following an application of water from rain or irrigation. For exact definition of the value used for field-capacity the following should be stated: The soil-texture, structure, uniformity and depth, the depth and rate of application of water, the temperature of the water, the degree to which evaporation and transpiration were eliminated in the test, the free drainage-conditions, the depth to the water-table, and the time elapsing after application of water that samples were taken. The length of time for a soil to reach field-capacity varies from 24 to 48 hours in sandy soils, five to ten days in silt clay-soils, and longer periods in clay-soils. Field-capacity is usually expressed as percentage of dry weight. The terms "capillary capacity", "maximum water-holding capacity", etc., have been used with essentially the same meaning as "field-capacity." (The term has been developed in soil-moisture investigations because the term "moisture-equivalent" is not representative of maximum moisture-content available for plant-growth in all soil-types. In view of the fact that slow downward movement continues after field-capacity has been attained, the adoption of this term as a hydrologic term is questioned by some members of the Committee, and its inclusion in this list is tentative pending the availability of some more acceptable term.)

Specific retention--The amount of water retained against the pull of gravity by rock or earth after being saturated. It is expressed as per cent by volume. It is sometimes erroneously stated to be synonymous with field-capacity of soils. It is a broader term than "field-capacity", being applied to all types of earth or rock. Its use is to determine the volume of water drained by the lowering of the water-table over a relatively long period of time as a result of pumping operations or seasonal fluctuation. "Field-capacity", on the other hand, is used to determine the amount of water available to plants within a short period after rain or application of irrigation-water, and may indicate the amount of water in the soil before complete drainage has taken place. If accurately determined, specific retention of a soil should indicate smaller equivalent values than field-capacity.

Permanent wilting-percentage--The moisture-content of the soil, expressed as per cent of dry weight, at which, with gradual reduction in the amount of soil-moisture, the leaves of plants first undergo a permanent reduction in their moisture-content from which they do not recover in an approximately saturated atmosphere without the addition of water to the soil.

Ultimate wilting-point--The moisture-content of the soil, expressed as per cent of dry weight, at which, with gradual reduction in the amount of soil-moisture, all of the leaves of the plant are completely wilted, and will not recover in an approximately saturated atmosphere without the addition of water to the soil.

Wilting-range--The range in moisture-content of the soil between the permanent wilting-percentage and the ultimate wilting-point.

Available water--The moisture-content of the soil above the ultimate wilting-point expressed as per cent of dry weight. (This is the moisture that can be extracted by plants. The range of available water is from the ultimate wilting-point up to field-capacity.)

Readily available water--The moisture-content of the soil above the permanent wilting-coefficient expressed as per cent of dry weight. (This is the moisture that can be readily extracted by the plant and used for normal growth.)

Initial moisture-deficiency--The amount by which the actual moisture-content of a given soil-zone (usually the root-zone) is less than field-capacity at the beginning of a rainy season.

Soil-moisture percentages--This term usually refers to percentages of moisture in the soil based on the weight of oven-dry material. Percentages on air-dry material or by volume are rarely used in present soil-moisture investigations, as they are not constant values.

Absorption

Absorption--The processes by which air or water enters the lithosphere, the latter either as vapor or liquid. The absorption of water includes (1) inflow of atmospheric water-vapor, (2) hygroscopic absorption, (3) wetting, (4) infiltration, (5) influent seepage, and (6) gravity-flow of streams into sink-holes or other large openings. Temporarily absorbed water reaches only the belt of soil-water or the intermediate belt of the zone of aeration, from which it escapes either by evaporation from film-surfaces or by root-absorption and transpiration from vegetation. Permanently absorbed water passes downward beyond the root-zone, finally reaching the zone of saturation where it becomes an increment to ground-water. The term "absorption" is also used to designate the quantity of water absorbed, and is expressed in depth of water (measured as liquid water) absorbed per unit of time--generally in inches or centimeters per day, month, or year.

Wetting--The process by which a liquid coming in contact with the dry (deficient in pellicular water) surface of a solid which attracts it, adheres thereto and forms a film thereon. One condition necessary for wetting is low contact-angle between the liquid and solid surfaces. Wetting to the point of pellicular satisfaction is necessary before film-flow can occur.

Spreading--The process by which a small amount of a liquid, as a drop, when placed upon the surface of another immiscible liquid, or upon a solid which it wets, will spread to a film. Liquids usually spread on solids only through the vapor, by evaporation from a drop and condensation to a film. Water, being relatively non-volatile, spreads very slowly. Spreading is not appreciably involved in the process of absorption.

Infiltration--The process by which liquid water enters the zone of aeration. It includes the formation and upbuilding of films around soil-grains through wetting by rainfall, melting snow, or temporary sheet-water, and the subsequent progressive downward movement of mobile water through the soil by film-flow after the demand for pellicular water has been satisfied.

Seepage--The process by which water percolates through the surface of the lithosphere. Influent seepage is seepage into the lithosphere where a zone of temporary or permanent saturation extends to the surface. Effluent seepage is seepage out of the lithosphere from a zone of saturation at springs or seepages.

Rainfall-penetration--The depth below the soil-surface reached by a given quantity of absorption from rainfall. Under arid and semi-arid climatic conditions, this depth frequently does not extend beyond the root-zone.

Water-spreading--Artificial absorption produced by spreading of surplus stream-flow over permeable soil by means of ditches, basins, pits, or wells.

Transpiration and evaporation

Vaporization--The process by which a liquid or solid changes to a gaseous state or becomes a vapor.

Evaporation--The process of vaporization at a temperature below the boiling-point. It is the principal process by which surface- or subsurface-water is converted to atmospheric water. It takes place whenever water in the liquid or solid state comes in contact with an unsaturated part of the atmosphere. The term "evaporation" is also commonly used to designate the quantity of water that is evaporated. Rate of evaporation is expressed in depth of water (measured as liquid water) removed from a specified surface per unit of time--generally in inches or centimeters per day, month, or year. As thus measured it may be considered as negative precipitation.

Evaporativity--The evaporating power of the atmosphere or the potential rate of evaporation with continuous water-supply. Rate of evaporativity is measured by plant physiologists in terms of weight units of chemically pure water lost per unit of time from some specified standard evaporating surface. For more general but less accurate use it is measured as depth of water removed from such a surface in unit of time.

Relative evaporation--The ratio of the rate of evaporation from a surface in contact with the atmosphere to the evaporativity under the existing atmospheric conditions, or the ratio of the actual to the potential rate of evaporation. When considered for a land-surface, transpiration, if any, is usually included with evaporation.

Interception of precipitation--The process by which precipitation is caught and held by foliage, twigs and branches of trees, shrubs and other vegetation, and evaporated from these surfaces.

Transpiration--The process by which water-vapor leaves the living plant-body and enters the atmosphere. It includes cuticular transpiration, or direct evaporation into the atmosphere from moist membranes through the cuticle; and stomatal transpiration, or outward diffusion into the atmosphere through the pores of stomata and lenticula of water-vapor previously evaporated from imbibed membranes into gas spaces within the plant.

Consumptive use--The quantity of water per annum used by either cropped or natural vegetation in transpiration or in the building of plant-tissue, together with water evaporated from the adjacent soil, snow, or from intercepted precipitation. It is sometimes termed "evapo-transpiration."

Retention--The amount of precipitation upon a drainage-area not escaping as surface stream-flow. It is the cumulative difference between precipitation and runoff, and represents evaporation, transpiration, subsurface-leakage, and, when short periods are considered, temporary surface- or ground-storage on the drainage-area. It closely represents consumptive use when considered for periods of a year or more.

REPORT OF THE COMMITTEE ON EVAPORATION, 1933-34

George F. McEwen, Chairman

Since the organization of this Committee two years ago, one member, Robert Follansbee, has resigned. The outline prepared to serve as a guide for work of the Committee was approved.

The present list of members follows:

G. F. McEwen, Chairman--Scripps Institution of Oceanography, La Jolla, California.
N. W. Cummings--San Bernardino Valley Union Junior College, San Bernardino, California.
R. E. Kennedy--State Engineer, Bismarck, North Dakota.
H. H. Kimball--1819 Monroe St., N.W., Washington, D. C.
Burt Richardson--Scripps Institution of Oceanography, La Jolla, California.
Carl Rohwer--United States Bureau of Agricultural Engineering, Fort Collins, Colorado.
Caleb Mills Saville--1026 Main Street, Hartford, Connecticut.
Thorndike Saville--New York University, New York, N. Y.
C. V. Theis--United States Geological Survey, Washington, D. C.

Owing possibly to the restrictive proposals as to the nature of this year's program, no manuscripts were submitted for presentation at the meetings of the Committee on Evaporation to be held on April 26 and 27, 1934, but the following papers have been published:

Geo. F. McEwen, Review of paper by R. Cherubim "Über Verdunstungsmessung auf See," Ann. Hydrogr., v. 59, Heft IX, pp. 325-335, 1931; J. Conseil Internat. Explor. Mer, v. 8, No. 1, pp. 106-108, 1933.
Carl Rohwer, Evaporation from free water-surfaces, Tech. Bull. No. 271, U. S. Dep. Agric., December 1931, pp. 1-96. [Evaporation at high elevations is given special attention.]
Carl Rohwer, Evaporation from salt-solutions and from oil-covered water-surfaces, J. Agric. Res., v. 46, No. 8, pp. 715-729, 1933.
Caleb Mills Saville, Some phases of Southern New England Hydrology, J. New Eng. Water Works Assoc., v. 47, No. 4, pp. 363-448, 1933. [While referring to evaporation, this paper deals especially with rainfall and runoff.]

Requests have come for various kinds of information regarding the subject of evaporation, especially in relation to practical engineering applications. These are summarized below:

(1) Specifications for a suitable set-up for measuring evaporation that would yield useful results without being too elaborate.
(2) How well do the self-recording Piche and Kassner-Fuess evaporimeters perform?
(3) Comments upon the evaporation-formulae of Thornthwaite (Geogr. Rev., October 1931).
(4) Is it possible to apply corrections to floating-pan readings to obtain the actual evaporation from a reservoir?
(5) What observations in addition to insolation, water-temperature, air-temperature, and relative humidity should be made for determining evaporation?
(6) What is the relation of the thickness of a layer of oil on water to the reduction of evaporation-rate, and what is the effect on temperature? How does the depth of water affect the result?
(7) What free water-surface temperatures are reached under prevailing conditions of sunlight and humidity in the arid west?
(8) What is the ability of an artificial lake of given depth and surface-area to dissipate the heat from condensers of an electric power-plant?

The above questions supplementing and in part duplicating the items listed in the tentative outline of work for the Committee, should receive careful consideration. A summary statement outlining answers as far as at present practicable would be welcome.

Scripps Institution of Oceanography,
La Jolla, California

REPORT OF THE COMMITTEE ON RUNOFF, 1933-34

LeRoy K. Sherman, Chairman

The members of the Permanent Research Committee on Runoff are as follows:

LeRoy K. Sherman, Chairman--8 East Huron Street, Chicago, Illinois.
H. K. Barrows--6 Beacon Street, Boston, Massachusetts.
Merrill Bernard--Bernard Engineers, Inc., Crowley, Louisiana.
W. L. Gerber--State Water Survey, Urbana, Illinois.
J. A. Harman--904 Jefferson Building, Peoria, Illinois.
W. W. Horner--International Building, St. Louis, Missouri.
R. E. Horton--Voorheesville, New York.
Clarence S. Jarvis--United States Engineer Office, Washington, D. C.
Carroll F. Merriam--Pennsylvania Water and Power Company, Lexington Building, Baltimore, Maryland.
F. Merryfield--Oregon State Agricultural College, Corvallis, Oregon.
Charles H. Pierce--United States Geological Survey, Washington, D. C.
J. C. Prior--Ohio State University, Columbus, Ohio.
J. W. Pritchett--State Board of Water Engineers, Austin, Texas.
Thorndike Saville--New York University, University Heights, New York.
J. C. Stevens--Spalding Building, Portland, Oregon.
Harold C. Troxell, United States Geological Survey, Los Angeles, California.

This report for 1933-34 includes three main topics: (1) Group-activities of the Committee; (2) researches and studies in hydrology by the individual members of the Committee; (3) notes of some work and publications relating to rainfall and runoff by other hydrologists.

Committee on Statistical Methods

On January 19, 1934, a conference attended by Messrs. Barrows, Cullings, Horton, Saville, and Sherman was held in New York. The important subject of "Statistical methods" in relation to frequency of rainfall and of flood-flow rates, which had heretofore been presented by Messrs. Merriam and Saville, was discussed. As a result, a Sub-Committee of the Committee on Runoff was formed, with Professor Thorndike Saville as Chairman, the other members being as listed in Appendix A attached. The functions of this Committee are especially important at this time in view of the proposed work involving statistical methods to be undertaken by Federal and other agencies. Chairman Saville will present a report on the plans of his Committee in Appendix A.

A Cooperating Committee on Rainfall and Runoff as an auxiliary to the Mississippi Valley Committee of the Public Works Administration--The Mississippi Valley Committee of the Public Works Administration, as one of its duties, has certain investigations relative to the hydrology of the Basin of the Mississippi above the Ohio. There is included flood-frequency, rainfall, and runoff as set forth in Public Works Administration Release 519. The work is to be done in collaboration with the United States Geological Survey. On March 21, 1934, Messrs. Saville, Sherman, and Horton addressed the Mississippi Valley Committee with reference to the aforesaid hydrologic work. The cooperation of the American Geophysical Union was invited. On April 12, 1934, the Committee on Runoff appointed a special Cooperation Committee as follows: W. W. Horner (St. Louis), Chairman; J. A. Harman (Peoria); A. F. Meyer (Minneapolis); Prof. G. W. Pickles (University of Illinois); L. K. Sherman (Chicago); Roy N. Towl (Omaha); and J. W. Woermann (United States Engineer Office, Chicago).

Reports by members of the Committee

Prof. H. K. Barrows--"I am having one of the students of the Massachusetts Institute of Technology make a thorough study of Sherman's paper on 'The hydraulics of surface-runoff' for thesis work."

Mr. Merrill Bernard presented a paper on "An approach to determinate stream-flow" (January 1934 Proc. Amer. Soc. Civil Eng.). Discussions of Mr. Bernard's paper have been presented to date by C. S. Jarvis and L. K. Sherman. Mr. Bernard applies the unit-graph principle to a number of Ohio streams. He uses what he terms a "Distribution-graph." He finds, on each basin he analyzed, that any particular ordinate (as, for example, the peak-rate of flow in a unit of time) has substantially a constant percentage of total volume of surface-runoff due to a unit-time rainfall and that this relation holds true (within limits) regardless of intensity of rain or rate of infiltration. Mr. Bernard's "distribution-graph" supports Sherman's unit-graph but offers a simple and preferable mode of expression.

Mr. W. W. Horner has a paper on "A study of rainfall and runoff on small urban area" (to appear soon in Proc. Amer. Soc. Civil Eng.). This study is based upon data collected during a period of over 20 years.

Mr. Robert E. Horton--"Hydrologic work particularly bearing on the question of runoff, in progress in my office and laboratory, includes the following:

"(1) A re-analysis of all of Rohwer's experimental data on evaporation (Tech. Bull. 271, U. S. Dep. Agric.) with special reference to determining the effect of wind on evaporation and the relation of evaporation to barometric pressure and elevation. The latter has an extremely important bearing on water-losses and runoff at high elevations.

"(2) A continuation of studies of rainfall-excess, outlined in paper on infiltration before the Section of Hydrology in 1933 (Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 446-460). In this connection, ten-year records, including all rain intensities, high and low, have been analyzed and rain-intensity versus duration curves have been plotted at representative stations throughout the country, thus making it possible to read off directly from the curves the approximate rainfall-excess, which is nearly the same as the surface-runoff, corresponding to any given infiltration-capacity of the soil in the vicinity of the rainfall-station.

"(3) A study of the hydraulics of the movement of flood-waves subject to friction-control. The flood-wave is treated as a mass of water superposed on the surface of the normal flow of the stream; its center of gravity is above that of the base-flow and it tends to fall to a uniform depth under the action of gravity. This tendency is resisted by channel-friction. It seems possible by analysis along this line to arrive at some fairly simple though approximate basis for determining the rate of flattening out and increase in length of a flood-wave as it passes down a river channel.

"(4) Studies of the analysis of the hydrograph are being continued to provide additional examples of ground-water depletion-curves and particularly to determine the ratio of ground-water runoff to total runoff in drainage-basins of different types, with different types of soil. It appears that the ratio of ground-water flow to total runoff affords an exceedingly simple and accurate numerical characterization of the type of regimen of a stream. For porous, sandy drainage-basins, where all the rainfall is absorbed, this ratio is unity and the streams have unusually steady flow. At the other end of the scale, for purely ephemeral streams, the ratio approaches zero.

"(5) A study has been made of the possibility of duplicating accurately the principal phenomena involved in runoff, including rainfall, infiltration, changes in soil-moisture, accretion and depletion of ground-water, and water-use by vegetation, by means of a mechanical model. A paper describing this model and the manner of its operation will be published shortly.

"(6) An exhaustive analysis has been made of velocity-distribution in stream-channels. This is perhaps more closely related to the work of the Committee on Channel Dynamics but it has a direct bearing on the methods and accuracy of stream-flow measurements and hence is related to the runoff-problem."

Mr. Carroll F. Merriam presented a paper on "Long-range forecasting" at the meeting in April 1934 of the Hydraulic Power Committee, Pennsylvania Electric Association. He gives a note of criticism and caution in the application of cyclic variation. At this same meeting Mr. Lohman presented further observations on the ground-water studies in Pennsylvania. Mr. Merriam refers to his work with E. S. Loane on comparison of flow-determinations on the Lower Susquehanna and states: "My contact with this work has made me feel keenly the need for more attention to statistical methods, and I hope that Professor Saville's Sub-Committee can be instrumental in showing what can and should be done to make rainfall- and runoff-records of greater value. I believe that in proportion to the expenditure that has already been made in the collection of these data, the cost of review would be small compared to the benefits to be derived."

Mr. C. H. Pierce, Senior Hydraulic Engineer, United States Geological Survey, briefly outlines a busy year in hydrologic work: "(1) A paper was prepared entitled 'Methods of gaging stream-flow' for the Lisbon meeting of the International Association of Scientific Hydrology. (2) Various scientific and technical problems were investigated relating to the operation and maintenance of about 2700 stream-flow measurement stations by the Water Resources Branch of the United States Geological Survey. (3) Special investigations were made regarding runoff and silt-movement at eight soil-erosion control-projects. These eight projects are located in the states of North Carolina, Kansas, South Carolina, Missouri, Texas, Washington, Oklahoma, and Wisconsin."

Professor John C. Prior, Ohio State University, writes: "During the last year I directed a Master's Thesis on 'The unit-graph method of obtaining runoff applied to selected Ohio streams.' This study was made by J. R. Smart who turned out a better-than-average student job and reached conclusions which I think will be of interest to you."

Mr. J. W. Pritchett, Texas Board of Water Engineers, was a member of a board directing a Civil Works Administration project in making studies of rainfall and runoff in Texas and devising formulae for peak-rates of runoff. A report on this study by R. C. Waggener, Mem. Amer. Soc. Civil Eng., is dated March 30, 1934. The rainfall versus runoff relation described by J. W. Shuman (Mon. Weath. Rev., May 1929) was used. Charts of long-time rainfall and stream-flow records are given for several Texas basins. The matter of statistical analysis and cyclic variation is favorably discussed. A bibliography of runoff and hydrological data was compiled by W. L. Rockwell.

Mr. L. K. Sherman during the past year completed a study to check the hypothesis as to a constant relationship between ordinates of flow and total volume of runoff. The study was made for a hypothetical basin where all of the physical elements, as well as rainfall- and infiltration-rates, were known. Under these conditions the analysis became a problem in hydraulics. This analysis (which confirms the hypothesis in wide limits) was presented by Mr. Sherman at a meeting of the University of Illinois Student Chapter of the American Society of Civil Engineers on March 28, 1934. Further reference to this work is made in Sherman's discussion of Bernard's paper and the work of Professor H. K. Barrows.

Professor Thorndike Saville writes: "During the year I have been conducting some studies relating to the application of different procedures for determining the probable frequency of flood-flows. Investigation has been made of five specific and different methods quite generally used. These methods have been applied to the long-term stream-flow record of the Tennessee River at Chattanooga, and have recently been extended to include the long-term records of the Tennessee at Florence and at Johnsonville, Alabama. The results thus far obtained indicate quite definitely that different procedures, all of them in quite common use, give very materially different estimates for the less frequent floods. It is quite evident that not all of the methods can possibly be correct. As the investigation has developed, it begins to appear as if none of the methods is based upon a very firm mathematical or philosophical reasoning. The estimates which one gets by the different methods, or even by the same method for different periods of time, vary materially. It is clear that a much more careful and analytical study of flood-frequency procedures should be undertaken."

Mr. John C. Stevens, Portland, Oregon, writes: "I have been working for some time on a recorder for snow and rain. My object has been to develop an instrument that would record precipitation whether in the form of rain, snow, or sleet at any place desired even though it be in isolated and inaccessible mountains. The recorder would be set up in the fall and would not be visited until the following spring if such were necessary. The record secured would be a graph of the accumulated precipitation in equivalent inches of water. There would also be a temperature-pencil that would make a continuous graph of the temperatures. We are just now setting up at Mt. Hood the fourth instrument, which embodies all of the improvements suggested by our experience with the earlier types." [Mr. Stevens expected to present a paper on this subject before the Section of Hydrology in 1934. He advises, however, that lack of snow this winter makes it necessary to defer his findings.]

Notes on runoff made during 1933-34 by other hydrologists

Major F. S. Besson in the "Military Engineer" (September-October 1933), presented a simple rational formula for peak-rates of runoff. It is based on the hypothesis used by Sherman and Bernard. It applies only to basins where an observed rainfall with a corresponding observed hydrograph of runoff is available. This formula is as follows: $Q_o/Q_m = C_o R_o/C_m R_m$, where Q_o, C_o, and R_o are the observed peak-rate of runoff, percentage-runoff, and depth of rainfall, respectively, Q_m is the required maximum peak-rate of runoff, C_m is a maximum percentage of runoff, and R_m is the given maximum depth of rainfall. R_o and R_m must have the same duration of rainfall. In the opinion of your Chairman this peak-rate formula is the best yet offered, subject to the limitations stated and subject to further analysis for storms of long duration.

Colonel C. R. Pettis, Fort Hayes, Columbus, Ohio, in the "Military Engineer" (January-February 1934), discusses Major Besson's paper. Colonel Pettis gives a comparison of results between his peak-runoff formula and that of Major Besson. In an interesting letter to your Chairman, Colonel Pettis says, "I can not go all the way with either you or Mr. Bernard, but I think that by improving our respective methods we will arrive at a point where our results are consistent." He forwards a paper titled "Flood-probabilities." This is based on his findings which comprised a study of all available published flood-records in the United States. Colonel Pettis has changed his formula to the form $Q = C\ (PW)^{1.25}$.

United States Bureau of Agricultural Engineering has prepared a set of rain-intensity diagrams showing maximum observed rain-intensities for different time-intervals up to 400 minutes and frequencies of different intensities for varying time-intervals for each of 207 stations of the Weather Bureau at which recording rain-gage records have been maintained. It is understood that these rain-intensity graphs are likely to be published in the course of the next three months. [See paper by D. L. Yarnell, High precipitation for short periods in the United States, published in present volume (Trans. Amer. Geophys. Union, fifteenth annual meeting, 1934).]

Mr. Tomihisa Iwasaki, Chief Engineer, Tokyo Water Works, presented a good example of the use of the draw-down or ground-water depletion-curve, related to antecedent rainfall, in forecasting dry weather stream-flow (J. Amer. Water Works Assn., February 1934).

Institute of Hydrology of Russia (U.S.S.R.)--The accompanying list of Russian hydrological publications was furnished by Robert E. Horton. Mr. Horton says, "These are so little known in this country that I think attention might properly be called to them in your report. The list given covers only a few of the papers bearing on stream-flow and runoff."

Liste des Publications de l'Institut Hydrologique de l'Etat

1--Bulletin de l'Institut Hydrologique

(Abstracted from copy from Dr. Brooks about January 16, 1934)

W. I. Altberg, Données nouvelles sur la nature de la glace de fond.
W. N. Walman, Méthode de prevision des variations de niveau des fleuves et des lacs employée par le Hydrografiska Byrân (Stockholm).
E. W. Oppokov, Sur la prédiction des crues du Dnièpre près Kiev.
W. N. Lébedew, Une méthode de la prédiction des crues de printemps sur les fleuves.

N. M. Bernadsky, Mécanisme, prédiction, et regularisation des crues fluviales.
E. W. Oppokoff, Essai de la prédiction de la hauteur du niveau d'eau du Dnièpre a Kiev.
D. I. Kotscherin, Ueber Wassermengekurven im Zusammenhange mit Feststellung des Wasserabflusses.
W. E. Timonoff, Formulaire d'une rivière à un seul courant.
F. G. Schmidt, Zur Theorie des Widerstandes einer ebenen Strömung.
W. I. Arnold-Alabieff, Eisdecke in den Hafengewässern von Leningrad im Winter 1922-23.
C. I. Strakhovitch, Sur un problème du mouvement d'un liquide visqueux incompressible.
M. A. Velikanox and D. L. Sokolowsky, On the climatic characteristic of the mean runoff.
M. A. Velikanov, The equation of energy for a turbulent stream.
A. M. Estifeev, On the alteration of the river regimen-curves after the withdrawal of water in a higher region.
D. I. Kocherin, Discharges and runoff of the River Oka at Kaluga.
M. A. Velikanov and M. J. Lvovitsch, Zur Berechnung des viel jährigen Mittelabflusses nach der Methode von Ad. Meier.
W. M. Rodevitch, Sur la classification des fleuves.
E. M. Sokolowa, Régime thermique du lac No. 2 dans la Courja inférieure.
E. M. Sokolowa, Evaporation d'eau de la surface du lac dans le bassin de la Kama.
W. E. Sotchewanov, Sur la dépendance d'evaporation de la surface d'eau.
W. E. Sotchewanov, Sur la dépendance d'evaporation de la radiation du soleil.
A. J. Goldstein, Sur les causes de la diminution du coefficient de la variation d'ecoulement annuaire en aval du fleuve.
K. I. Strakhovitch, Sur le problème du mouvement a tourbillons libres.
V. M. Makkaveyev, A theory of "mixing phenomena" accompanying the turbulent motion of fluid in open channels and questions of the winter flow of rivers.
L. V. Kazanskaya, Investigation of water percolation through a layer of gravel.
B. B. Davison, On the permanent motion of the ground-water through a prismatical dam of rectangular cross-section.

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APPENDIX A--REPORT OF THE SUB-COMMITTEE ON STATISTICAL METHODS

Thorndike Saville, Chairman

The Committee on Runoff, Section of Hydrology, American Geophysical Union, at a meeting held in New York on January 19, 1934, authorized the formation of a Sub-Committee on Statistical Methods as applied to hydrology. Subsequently, the Sub-Committee was constituted as follows (cooperating members, not members of the Section of Hydrology, being indicated by (+) following the name): C. C. Babb(+); J. H. Folse(+); H. A. Foster(+); L. Standish Hall; G. F. McEwen; C. F. Merriam; Fred Merryfield(+); S. L. Moyer(+); Thorndike Saville, Chairman; J. J. Slade(+); A. Streiff; and J. D. Watson(+).

The Sub-Committee has been able to hold no meetings since its formation, but has adopted a tentative program of work which is outlined in attached Appendix A-1.

There has been a great increase in the number of papers presented before the Section of Hydrology and before other technical and scientific societies utilizing statistical methods in the interpretation of hydrological data. The Sub-Committee conceives that its first task should be directed toward a coordination and logical exposition of the various methods which have been proposed for the statistical analysis of hydrological data. In the initial stages of its program, the Sub-Committee proposes to allocate to its various members different specific subjects related to hydrology in the interpretation of which statistical methods have been commonly used. Such subjects as analyses of rainfall- and runoff-data, including duration-curves, frequency-distributions, etc., will be studied. Empirical formulae will be investigated as to their applicability to specific types of hydrological data. One of the immediate objectives of the Committee will be to try to determine what empirical methods which have been utilized in the past have been proven to be unsatisfactory under certain given conditions. A later effort will be made to develop methods which can be proved to be applicable to certain given conditions. The general program for the immediate work of the Sub-Committee is set forth in attached Appendix A-1.

APPENDIX A-1--TENTATIVE PROGRAM FOR SUB-COMMITTEE ON STATISTICAL METHODS, COMMITTEE ON RUNOFF, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

(I) Compilation of statistical methods used in hydrological studies including: (a) Empirical formulae; (b) statistical arrays, including frequency-curves and correlation-procedures; and (c) semi-empirical methods. [Note--To different members of the Sub-Committee will be allocated responsibility for compiling data under the above headings relating to such subjects as rainfall, stream-flow, evaporation, ground-water, floods, transpiration, etc.]

(II) Application of methods in (I) to specific data to determine: (a) Methods of local applicability; (b) methods of general applicability; and (c) methods proved obsolete, false, or misleading. [Note--Conclusions from this item must be substantiated by actual examples subjected to critical analysis. Possibly a questionnaire to members of the Section would be productive of many helpful suggestions bearing on experience with different procedures developed from item (I).]

(III) Preparation of a manual for statistical methods applied to hydrology: Such a manual, with numerous applications of various methods to actual problems, describing procedures and pointing out limitations and interpretations would be most helpful and would stimulate a more wide-spread use of proper statistical procedures with resultant improvements and advances over present practice. This is an ultimate objective of the Sub-Committee's activities to be consummated only after a considerable period.

REPORT OF THE COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1933-34

F. J. Veihmeyer, Chairman

The members of the Committee on Physics of Soil-Moisture include the following:

F. J. Veihmeyer, Chairman--College of Agriculture, Univ. of California, Davis, Calif.
F. J. Alway--University of Minnesota, University Farm, St. Paul, Minnesota.
T. F. Buehrer--University of Arizona, Tucson, Arizona.
J. S. Cole--Bureau of Plant Industry, Department of Agriculture, Washington, D. C.
J. A. Dennison--National Bureau of Standards, Washington, D. C.
N. E. Edlefsen--College of Agriculture, University of California, Davis, California.
H. J. Fraser--International Nickel Company, Sudbury, Ontario, Canada.
O. W. Israelson--Utah Agricultural Experiment Station, Logan, Utah.
G. E. Ladd--United States Bureau of Public Roads, Washington, D. C.
P. G. Nutting--United States Geological Survey, Washington, D. C.
J. C. Russell--University of Nebraska, Lincoln, Nebraska.
W. O. Smith--6716 Thomas Boulevard, Pittsburgh, Pennsylvania.
E. A. Willis--United States Bureau of Public Roads, Washington, D. C.

The Committee has attempted during the past year to obtain information on the usefulness of soil-moisture functions and constants. Members of the Committee and others who have been engaged in soil-moisture studies were asked to give their opinion as to the usefulness of soil-moisture functions and so-called constants listed below with which they had worked.

The idea is to bring out the limitations, misconceptions, or erroneous applications as well as the correct use of the various soil-moisture functions and constants, both for engineering and agricultural purposes.

Most soil investigators readily recognize that some of the items listed are constants whereas others are functions of the moisture-content. Some are defined in an arbitrary way while others are founded on basic concepts.

Those who contributed to this report are as follows: F. J. Alway, University of Minnesota; M. S. Anderson, Bureau of Chemistry and Soils, United States Department of Agriculture; L. D. Baver, University of Missouri; H. F. Blaney, Bureau of Agricultural Engineering, United States Department of Agriculture; G. B. Bodman, University of California, Berkeley; H. G. Byers, Bureau of Chemistry and Soils, United States Department of Agriculture; I. A. Denison, National Bureau of Standards, United States Department of Commerce; N. E. Edlefsen, University of California, Davis; H. J. Fraser, Sudbury, Ontario; W. Gardner, Utah State Agricultural College; S. S. Green, City of Los Angeles Department of Water and Power, Los Angeles; A. H. Hendrickson, University of California, Davis; R. E. Horton, Consulting Engineer, Voorheesville, New York; C. H. Lee, Consulting Engineer, San Francisco, California; H. E. Middleton, Bureau of Chemistry and Soils, United States Department of Agriculture; M. L. Nichols, Alabama Polytechnic Institute; L. B. Olmstead, Bureau of Chemistry and Soils, United States Department of Agriculture; A. M. Piper, United States Geological Survey, Department of the Interior; O. J. Porter, Division of Highways, California Department of Public Works; G. E. P. Smith, University of Arizona; W. O. Smith, Pittsburgh, Pennsylvania; T. E. Stanton, Division of Highways, California Department of Public Works; F. J. Veihmeyer, University of California, Davis; E. A. Willis, Bureau of Public Roads, United States Department of Agriculture; and J. D. Wilson, Ohio Agricultural Experiment Station.

Capillary potential--Defined by Buckingham [see reference 16 under "Literature cited" at end of this report] and later by Gardner [20]. Gardner makes the general comment that the soil-moisture problem is essentially one in mechanics and the constants which are significant are those that would appear logically in a set of dynamical equations. He thinks that numerous factors seem to enter implicitly but he feels that the introduction explicitly of these adds great difficulty to what otherwise is a comparatively simple problem.

Piper calls attention to the limited amount of work which has been done on the relation of the capillary potential to other physical properties of the soil, and thinks that to many investigators the term capillary potential is confusing.

Veihmeyer and Hendrickson state that so far as they are aware no porous-cup potentiometers have yet been developed that are capable of measuring the capillary potential when the height of the liquid in the potentiometer is greater than that due to a pressure of one atmosphere. Their investigations do not support Richards' [34] statement that optimum soil-moisture conditions for most of the agricultural plants lie within the range between zero and one atmosphere. They find that plants seem to grow equally well within a range of from 0 to 16 atmospheres. Until the capillary potential of soils can be measured through this range they say that its usefulness to plant investigators is very limited. Veihmeyer and Hendrickson further point out that the auto irrigator of Livingston [25] and the porous-clay apparatus of Richards [34] fail to give a uniform distribution of water in the soil and that relatively low moisture-contents cannot be maintained in soils on which plants are growing.

Bodman believes that the difficulties in the way of the measurement of the capillary-potential function and transmission-function are considerable, but that field-measurements appear hopeful and that the measurements of these functions will probably be reduced to one of routine and their utility generally accepted. At present they are part of the most rational line of reasoning which can be used in connection with soil-moisture investigations.

Edlefsen thinks that the capillary-potential concept is extremely useful in attempting to develop a rational picture of the soil-moisture system. Methods have not yet been developed for measuring this quantity over the entire range of moisture-content used by the plants, but results from his experiments indicate that a field-method of measuring this quantity over the entire range of moisture-content may be possible. This quantity indicates, from the standpoint of the plant investigator, the amount of energy per unit mass of water that must be supplied in order to transpire water. In addition, it is useful in a study of the movement of soil-moisture since the gradient of this function is the driving force. It is much better to make use of well-established elementary physical concepts than to attempt to develop a new science in the study of soil-moisture. The capillary potential is defined in such a way that it is a function of the soil and its moisture-content with the possibility of some other quantities, such as temperature, introduced implicitly. Some other arbitrary functions that are in current use in soils to some extent are defined in terms of the method of making the measurement and the result may depend upon the procedure used in making the measurement and to only a small degree upon the soil which is being tested.

Flow of water in soils--Gardner says that the Slichter [38 and 20] transmission-constant is very important in connection with the work done on transmission of water in soils.

Edlefsen says that the transmission-function is based on elementary physical notions and is useful in dealing with the soil-moisture system although, from an experimental standpoint, it has been investigated but slightly. However, with suitable methods developed for measuring the capillary potential, this quantity will no doubt be studied more thoroughly and hence may become more useful in practice. As a first approximation, it has been assumed by Gardner that this quantity is proportional to the quantity of the water present in the soil. The proportionality-constant has been termed the transmission-constant. Richard's results indicate that this function is not a linear one for the soils with which he worked and therefore it may be necessary to use more than one transmission-constant in characterizing the transmission-function of the soil.

Fraser refers to a recent paper by Fair and Hatch [19] in which equations are presented for the permeability of stratified and unstratified sand-filters and says he has checked the equations against his experimental data on spheres and found a close agreement between experimental and calculated permeabilities for grain-sizes less than 1.5 mm. For larger grain-sizes, the equations gave values increasingly lower than the experimental values (in terms of loss of head). This probably is due to the increasing importance of turbulent flow in the large pore-spaces.

Lee believes that the transmission-constant used by Slichter, or the permeability-coefficient as it has more recently been used, is very useful in ground-water studies and in investigations of foundations and earth dams. The laboratory determination of permeability-coefficient is a much more practical and accurate determination of subsurface-flow than that possible by Slichter's or Hazen's method according to Lee.

Horton says that he has found the following to be most useful: Transmission-constant or transmission-function, capillary potential, permanent wilting-percentage, moisture-equivalent, and field moisture-capacity. Horton uses the infiltration-capacity [22] which he says is not quite the same as the transmission-capacity but is closely related to it.

W. O. Smith [42] discusses the relation of vapor-pressure to the mechanism of soil-moisture transfer and points out that liquid is deposited in a soil either by the passage of a capillary meniscus through the soil or by a sorption process. In the first case, the amount of liquid placed depends entirely on the manner of drainage. After it is placed, a temporary adjustment takes place. Whatever flow takes place occurs at this stage. Liquid flows to the parts of the grains where it can exist stably, for example, the simple rings of liquid at contact-points. Smith believes that all further adjustments are by distillation and condensation, and that these processes are responsible for the slow movement and migration of soil-moisture rather than any flow over the grain-surfaces which occurs only in the initial stage of moisture-adjustment and then only locally. Smith calls attention to three papers [39, 41, and 40] in which the mechanism of the penetration of a continuous meniscus into a soil-body is discussed.

Denison reports that the permeability of soils to air is important in studying corrosion. The moisture-equivalent, water-holding capacity, volume-weight, total pore-space, and volume of voids are used to measure permeability quantitatively. He finds that the greater the permeability of an acid soil, the greater is the tendency for corrosion on the surface of ferrous materials to take the form of pitting. In certain soils, which according to physical measurements were very impermeable, very slight pitting has occurred even after long periods of burial, although their acidity was such as to indicate severe corrosion. A paper by Denison and Hobbs on the "Corrosion of ferrous metals in acid soils" giving the details of the physical measurements of soil-permeability will appear shortly in the Bureau of Standards Journal of Research.

Willis states the Bureau of Public Roads has found the coefficient of permeability to be useful in the design of drainage-systems and in computing the amount of water transmitted by a soil-layer or soil-body. The rate of capillary flow has an important bearing on the occurrence of heaving due to frost. The rate at which water is drawn into highway subbases when evaporation is prevented by a water-tight surface controls to a large degree the behavior of the base; consequently, an evaluation of this factor by means of suitable tests assists in the selection of materials for base-courses and subgrades.

Green says that in determining the suitability of soils for use in the rolled fill-section of a dam the percentage of consolidation under vertical loads and the permeability of the consolidated soil should be obtained. The soil is compacted in a consolidation-percolation cylinder [32] and the soil-column is then subjected to percolation.

Lento-capillary point as defined by Widtsoe and McLaughlin [51]--Bodman states that at present he is unwilling to admit of the existence of such a point, at least in the region usually attributed to it, but that there appears to be a characteristic moisture-content for some soils at which the rate of movement undergoes a sharp change.

Piper believes that the lento-capillary point is more or less equivalent to specific retention but he feels that the distinction made by Widtsoe and McLaughlin fails from a weakness in laboratory procedure in that the drained column of soil is exposed to the air and is not in contact with a continuous body of permeable material extending to a remote water-table.

Veihmeyer and Hendrickson question the existence of the lento-capillary point since they find that after soils are drained to the field-capacity as defined by them [46], the rate of downward movement of water very markedly decreases. In all of their experiments the extraction of water by plants was found to be tremendously greater than the very slow drainage after the field-capacity is reached. They found that there was no significant point in the plant soil-moisture extraction-curve in the region suggested for the lento-capillary point at which transpiration or plant-growth seemed to be affected.

Moisture-equivalent as defined by Briggs and McLane [14]--Bodman has found this to be exceedingly useful as an indicator of the moisture-content at which rate of water-movement in a combined capillary and gravitational field is sharply diminished, but believes that a standard method of determination should be strictly followed. He also calls attention [11] to the usefulness of the moisture-equivalent as a textural index for field-classification.

Veihmeyer [48 and 49] points out the need for standardization of the method of determining the moisture-equivalent. Veihmeyer and Hendrickson [46] also point out that, for fine-textured soils, the moisture-equivalent is a fair measure of the field-capacity, the moisture-content at which the rate of downward movement of water markedly decreases. They also show [44 and 45] that the moisture-equivalent cannot be used to calculate the residual moisture in the soil at permanent wilting, the permanent wilting-percentage.

Willis [21] lists the moisture-equivalent among the important tests used in highway engineering, Denison uses it in his soil-corrosion studies, Horton uses it in his water-supply work, and Lee says it is valuable for soils in which it closely approaches the field-capacity but is not so useful when it differs materially from the field-capacity. Lee also says that standardization of the moisture-equivalent determination is essential for usable results. Piper believes that the usefulness of the moisture-equivalent scarcely needs proof, but stresses the fact it is not a physical constant and its magnitude is dependent upon strict adherence to a definite technique.

Middleton thinks the moisture-equivalent is the most useful of the constants listed. Since it shows the approximate field-moisture carrying capacity of the soil and by the use of an appropriate factor it shows the wilting-coefficient of the soil, the difference between the moisture-equivalent and the wilting-coefficient being the amount of moisture available for plant-growth. He also uses the moisture-equivalent to judge the erosiveness of soils [27 and 28].

Alway uses the moisture-equivalent to evaluate the moisture relations of soils when he works with large numbers. He thinks that, while the hygroscopic coefficient does not give values so closely concordant as those obtained with the moisture-equivalent, it gives much more definite information as to the available moisture-content of soils [1, 2, and 3].

Blaney finds the moisture-equivalent to be of little use for sandy soils because it does not agree with the field-capacity. However, he finds it useful for average soils, but prefers to use field-capacities determined in the field.

Stanton and Porter think that the moisture-equivalent is quite useful for identification purposes but it is probably more useful from an agricultural than from an engineering standpoint. They feel that while a definite relation has been reported between the moisture-equivalent and the amount of water soils will take up in the field, which may be more or less true for surface-conditions, this interpretation is erroneous for all conditions.

Field-moisture equivalent as defined by Hogentogler, Wintermyer, and Willis [21]--Willis lists the field moisture-equivalent as one of the important tests made in soils in highway engineering. Stanton and Porter believe that the field moisture-equivalent falls into the same class with the centrifuge moisture-equivalent in that it is useful in identification of soils but does not reflect directly the construction properties of the material. They say that the field moisture-equivalent is much more subject to personal equations than the centrifuge moisture-equivalent because the results depend upon the judgment of the operator rather than a definite specified treatment, but it is useful in determining, as near as possible, a definite state from which to start shrinkage-tests.

Xylene-equivalent--Middleton's is the only comment on the xylene-equivalent, defined as the weight of xylene held by 100 grams of oven-dry soil in a centrifugal field of 1000 g. determined under standard conditions. He says it has never been determined in his laboratory since he believes the use of the xylene-equivalent in determining the water of imbibition is based on a misconception. He thinks it would be invaluable in the study of the water-relations of soil-colloids if it were possible to determine the water of imbibition by this method.

Freezing-point depression--Bodman has experienced difficulty in making precise measurements of the freezing-point depression on the most interesting range of soil-moistures, at about the wilting-point. Compression of the thermometer bulb and necessary manipulation of the soil, among other things, may cause very serious errors. He states that, while the method is fundamentally sound, the difficulties are experimental. Edlefsen makes practically the same comments and points out that the freezing-point can only be measured successfully at high moisture-contents.

Veihmeyer has been able to make freezing-point depressions on some soils at or below the permanent wilting-percentage. On others difficulty was encountered. He has attempted to extend the freezing-point depression curve to low soil-moisture contents by means of dilatometer measurements but the results have been unsatisfactory.

Water-vapor adsorption--Edlefsen says that water-vapor adsorption at 100 per cent relative humidity is of practically no value since the temperature must be controlled extremely accurately for long periods of time before equilibrium can be reached. Middleton and Bodman call attention to the same difficulty. Gardner points out Linford's [24] objection to the use of this value, and Bodman and Veihmeyer call attention to Puri's work [33]. Bodman says that the conditions prescribed in the determination of the hygroscopic coefficient cannot be obtained. Middleton states that he does not make water-vapor adsorption at 100 per cent relative humidity. Veihmeyer and Hendrickson [47] question the use of the hygroscopic coefficient or any values of water-vapor adsorption at different relative humidities for calculating the permanent wilting-percentage or the amount of readily available water in soils.

Bodman thinks that the impossibility of attainment of an equilibrium state was well recognized by some of the early workers with the hygroscopic coefficient. Their use of this method in which an arbitrary time was chosen on an adsorption-time curve was as legitimate as the selection by others of an arbitrary centrifugal force on a water retention-force curve. The former is possibly more to be criticized because of its more difficult reproducibility. He thinks that the use of the hygroscopic coefficient has been well justified.

As mentioned above, Alway thinks the hygroscopic coefficient is a better measure of the available moisture-content of soils than the moisture-equivalent.

Middleton uses water-vapor adsorption at 99 per cent relative humidity (over 3.3 per cent H_2SO_4 by weight) as a measure of the colloid-content of soils [35] and believes this a more reliable determination than the hygroscopic coefficient and can be used for the same purpose as the hygroscopic coefficient. Bodman says that adsorption of water-vapor at 99 per cent relative humidity for colloid-content is empirical and arbitrary. He found that colloids separated from five California soils conform closely in adsorption at this humidity to those described by Robinson [13]. He says that the so-called colloid-content determination by this method is a better indicator of much physical behavior than that by sedimentation-analysis [12]. He states that contents of alkali salts of about 0.4 per cent may seriously affect the amount of adsorption.

Middleton says that water-vapor adsorption of soil-colloids at 75 per cent relative humidity is useful in differentiating colloids from different types of soil [5] and that the ratio of the water-vapor adsorption of soil colloids at 99 per cent to that at 75 per cent humidity is useful in classifying soil-colloids [15]. Middleton uses water-vapor adsorption at 50 per cent relative humidity only in an experimental way, and says that in dealing with air-dry soils where the amount of water contained is an important consideration, it is convenient to have them in equilibrium with an atmosphere of 50 per cent relative humidity. Bodman finds that a useful qualitative measure of the colloidality (referred to 3.3 per cent H_2SO_4) can be obtained by simple air drying at about 50 per cent relative humidity, but does not think that it can have any particular utility from the physiologist point of view.

Veihmeyer and Hendrickson [47] have tested many soils for water-vapor adsorption at different relative humidities. The permanent wilting-percentages of these soils were known and the ratio of the values of adsorption to the permanent wilting-percentages were far from constant. They also find that the adsorption-value versus soil-moisture curves in some cases cross over each other which indicates the futility of attempting to calculate any soil-moisture content such as the permanent wilting-percentage from adsorption-values by the use of a factor.

W. O. Smith will shortly publish in "Physics" his studies on the adsorption in an ideal soil and describes the distribution of the adsorbed vapor in the soil during hydration and dehydration.

Vapor-pressure relationships--Edlefsen has developed [17 and 18] a method for measuring vapor-pressure over the entire range of moisture-content with moderate degree of accuracy. He finds this quantity very useful in studying the soil-moisture system. It is related by dynamical equations to the capillary potential and therefore when one quantity is known the other may be calculated.

Byers thinks that vapor-pressure measurements on soils containing amounts of moisture equal to or in excess of the hygroscopic coefficient would have little value, but those on soils below the hygroscopic coefficient ought to have considerable value if made under proper conditions but their value would be with reference more to the chemical characteristics of the colloid than in other directions. He says that extensive study of water-vapor adsorption under various conditions would be rewarded with increased knowledge of the behavior of colloids in the field especially with reference to irreversible dehydration. Bodman says that the static method of determining the vapor-pressure versus moisture-content curves for soils and extracted colloidal clays is simple and probably serves more completely than any other one soil-moisture function to characterize a soil. The chemical composition with all its associates and dependent physico-chemical properties, may be predicted in part from such a curve. He has obtained evidence of what is commonly called hysteresis behavior for some soils by the static method. Veihmeyer and Hendrickson [47] have also noted similar effects.

Heat of wetting--Baver states that the heat of wetting and adsorption of water-vapor at 100 per cent relative humidity gave practically the same results as far as their use is concerned in interpreting the surface activity of the soil. These measurements cannot be expected to be used as a single-valued determination because the results are affected by the chemical nature of the clay, the nature of the ion on the exchange complex, the presence of organic matter, and the clay content itself.

Baver believes that the curve showing the adsorption of water as related to vapor-pressure will be more valuable than any one particular humidity. He has reported [6 and 9] variations in the heat of wetting and water-vapor adsorption.

Anderson says the heat of wetting is an accurately determinable value for soils and soil-colloids when carried out under proper conditions [4]. The values obtained vary not only with the quantity but with the character of the colloid. He finds [5] heat-of-wetting values parallel the water-vapor adsorption over 30 per cent sulphuric acid or at 75 per cent relative humidity.

Edlefsen states that heat of wetting is related dynamically to the capillary potential, vapor-pressure, and freezing-point depression, and therefore is a useful concept. Experimentally it is useful only in studying the soil at low moisture-content since the change in heat of wetting over the range of soil-moisture content used by plants is too small to be measured successfully with present methods.

Rate of drying--Baver [10] has studied the rate of drying as affected by temperature in various colloidal clay systems and has found that this method of studying clays will probably be of much value in determining the nature of the clay complex. Edlefsen thinks that the rate of drying concept only has qualitative value since the mechanism of drying has not been worked out thoroughly.

Permanent wilting-percentage as defined by Veihmeyer and Hendrickson [45]--Veihmeyer and Hendrickson point out that the permanent wilting-percentage is different from the Briggs and Shantz wilting-coefficient because by definition the wilting-coefficient bears a definite relation to the moisture-equivalent. They believe that the permanent wilting-percentage is the most important soil-moisture condition from an agricultural standpoint since it is the condition which limits the normal activities of plants [43]. The permanent wilting-percentage is the lower limit of readily available soil-moisture. They have shown [47] that the permanent wilting-percentage is remarkably constant for any given soil under any evaporation-condition likely to be obtained with plants growing in the field.

Lee believes that the permanent wilting-percentage is particularly useful in the study of transpiration and rainfall-absorption. Horton lists the permanent wilting-percentage together with field moisture-capacity as being important in his work. G. E. P. Smith considers this moisture-condition to be of extreme importance if it is determined by actual growing of plants under controlled conditions.

Blaney reports that he uses various terms such as wilting-point, wilting-coefficient, and wilting-percentage, but there is some question as to their practical value in experiments made under field-conditions. He says the term wilting-coefficient as defined by Briggs and Shantz is not usually applicable to the soils he has investigated in southern California. He believes the term permanent wilting-percentage is the best one now in general use, but he seldom uses it. He suggests another term, "ultimate wilting-point," to indicate the soil-moisture content at a stage of wilting more advanced than that defined for "permanent wilting."

Alway is very skeptical as to the value of the permanent wilting-percentage as anything like a routine operation because he believes the amount of water remaining in the soil when plants wilt permanently depends on various external conditions.

Water-supplying power as defined by Livingston and Koketsu [26]--Wilson uses the soil-point method of studying the water-supplying power of soils. He refers to various publications of Livingston and his coworkers [50] on the use of evaporation criteria as a determinant on the time at which water may be added artificially to keep plants always in good condition. He points out that the influence of temperature on the water-supplying power of a soil has not been considered to the extent its importance deserves.

Dielectric constant--Edlefsen points out that this quantity is well known, although it has been used to only a slight extent in the study of soil-moisture. He has secured results that indicate that it furnishes a basis for measuring the quantity of water in soils and also a basis for developing apparatus for the measurement of the capillary-potential function over the entire range of soil-moisture. Olmstead mentions work of Burton and Pitt at Toronto in which they measured the moisture-content of clean sand by means of the dielectric constant but failed with soils from their garden.

Functions that are related to physical properties of soils--Lee refers to his discussion [23] of soil as a basic material of construction in which he lists the soil-properties which he has found to be useful in his work.

Bodman calls attention to the lack of clearness in the use of the term compressibility and to the high correlation between the soil-properties associated with consistency and the moisture-equivalent [12 and 31]. Bodman, in his comment on plastic limits, says that for a given moisture-content the amount of flow varies with the applied force. The converse is also true. Hence, he says, the "fliessgrenze" of Atterberg has no real meaning unless the conditions are specified [13] and this point does not appear to have emerged during the inclusive adoption of the so-called Atterberg constant by American soil-workers. As with other soil-constants, however, an empirical determination of the Atterberg type in the form of impact-moisture-content curves appear to have some utility. He suggests it as a measure of "stiffness" [13]. Bodman says that the rolling-out limit needs much refinement, although its simplicity is thereby destroyed [37]. He does not agree with the method of obtaining the shrinkage-limit by extrapolation of the linear part of the moisture-content versus volume curve.

Olmstead says that the plastic limits of a soil are usually considered to be the moisture-contents at the "fliessgrenze" and the "ausrollgrenze" of Atterberg but that these constants are not usually determined by straightforward physical method but depend upon personal judgment. He thinks the method has been partially mechanized for determining the upper plastic limit, but the literature reveals no intercomparisons nor standardization of these methods. When the hand method of Atterberg is used, fairly concordant results for this value should be obtained by different workers if the tapping is not too gentle. Determinations of the lower plastic limit give results that are in closer agreement than obtained for the upper plastic limit. Olmstead says a few agricultural uses have been made of plastic limits. While, in general, the plasticity-numbers agreed with the field-designations of consistence, the agreement was not close enough to assign plasticity-ranges to consistence descriptions. It is apparent that plastic limits can be reproducibly determined. However, they are arbitrary points upon whose numerical values different workers do not agree. They will, however, usually arrange a series of soil-samples in about the same order of ascending plastic range. Better methods, universally adopted, appear to be needed before much progress can be made in agricultural usage. Olmstead believes that one reason why the plastic limits have been found useful in road construction is that the determinations have mostly been made in the laboratory of the Bureau of Public Roads where the procedure is exceptionally proficient. He refers to Russel's statement [36] to the effect that the shortcomings of the Atterberg methods are due to the lack of agreement on details of technique. The whole field of consistency-phenomena in soils needs elucidation. Until that is done the value of Atterberg's constants is questionable.

Olmstead calls attention to the wide discrepancies found in sticky-point measurements reported by Keen and points out that although workers in many soils-laboratories have considered the sticky point, little in the way of practical results seems to have been obtained. If the moisture-equivalent, or permanent wilting-percentage, for example, could not be determined by different workers with any better agreement than were the sticky points of the two soils reported by Keen, Olmstead thinks we should regard these determinations as of practically no value.

Middleton thinks that shrinkage-limit of soil is an important consideration from both an engineering and an agricultural standpoint, but that the methods of determining shrinkage-limits are largely empirical and depend to a considerable extent upon the personal equation. He has hopes of developing a method of measuring shrinkage of soils in which the moisture-content and degree of packing of the soils will be reproducible and in which the personal equation will be almost entirely eliminated. Baver believes that the plasticity-limits have more possibilities for characterizing soils than has been credited to them [8]. He refers to work by Nichols and himself in which the plasticity-limits have been correlated with the coefficient of friction, compressibility of the soil, and cohesion. They have been interested in dynamic properties of soils involved in tillage. They find that plastic limits are associated quite closely with such moisture-relationships as moisture-equivalent, and hygroscopic coefficient. They have developed a method for measuring the upper plastic limit [7]. Baver's experience with sticky point has been most discouraging. He questions whether the sticky point has a high degree of correlation with most soil-properties.

Nichols believes that the coefficient of friction is of greatest importance in tillage-studies. He says that cohesion is a property which enters into practically all of the other soil-reactions. He refers to his studies on dynamic properties of soils [29 and 30]. Nichols believes that one of the most valuable constants is the Bouyoucos colloidal determination with the hydrometer for non-plastic soils, but believes that it should be called the "hydrometer-constant" instead of the colloidal constant.

Willis states that internal friction and cohesion in combination are important factors in controlling the stability and bearing power of soils. He finds it is possible to estimate with a fair degree of accuracy the bearing power under different conditions of bearing area and surcharge or adjacent load, the factor of safety against sliding in cuts and fills, and critical height of slope in cut and fill. Wherever there is actual permanent movement of one part of a body of soil with respect to another, internal friction and cohesion enter into the mechanics of the reaction. Practically it is possible to use these functions only in estimates because of the nonuniformity of soil-deposits and because of certain assumptions which must be made in the theoretical analysis. Elaborate testing equipment is required for the determination of the angle of internal friction and coefficient of cohesion. He states that compressibility and elasticity are of particular importance in foundation analysis [21].

Willis believes that the usefulness of the plastic limits, shrinkage-limit, and the moisture-equivalent lies primarily in the relationship which they bear to one another. Individually they serve as qualitative indicators of the properties possessed by soils. Collectively they form a highly satisfactory basis for the identification of soils for engineering purposes [21].

Stanton and Porter believe that the coefficient of friction is one of the important characteristics of soil from an engineering standpoint. Their tests on undisturbed samples follow a method similar to that suggested by Terzaghi. They believe that cohesion properties of a soil reflect the sheering strength under certain conditions and therefore are helpful in determining supporting-value. Additional investigation is necessary in order to perfect methods of test for both cohesion and internal friction. They believe that resistance to penetration is a relative measure of consistency and bearing capacity of soils. It reflects to some degree both internal friction and cohesion. Results, however, cannot be interpreted to reflect supporting value directly for all types of soils and conditions of surcharge where the size and shape of loaded area is different from that covered by the test. They believe that their penetration or bearing test furnishes a relative measure of supporting value of roadway surfacing materials where the surcharge is low and the size of the loaded area is small. They think that compressibility is an important characteristic from an engineering standpoint. A satisfactory method for determining the probable compression or settlement of a foundation or embankment is, therefore, necessary in order to properly design and construct both highway bridges and fills. They think that soil tests should be divided into two groups: (1) Tests having a direct effect upon roadway construction and which determine characteristics such as cohesion, internal friction, compressibility, permeability, elasticity, volume-change, and capillarity; and (2) tests which do not necessarily reflect any particular desirable properties in themselves but which may be used at times to good advantage in classifying and identifying soils.

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REPORT OF THE COMMITTEE ON UNDERGROUND-WATER, 1933-34

David G. Thompson, Chairman

Activities of the Committee

The by-laws adopted at the meeting of the Section of Hydrology in 1933 provided that the membership of research committees should be reconstituted every three years. There have, accordingly, been some changes in the membership of the Committee on Underground-Water. Certain members have retired because of pressure of other duties or because they are no longer actively engaged in ground-water work. Dr. O. E. Meinzer, who retired as Chairman of the Section of Hydrology, has agreed to serve on the Committee, and probably two or three other men will be appointed to make contact with special phases of the field covered by the Committee. It is with regret that the Chairman reports the loss to the Committee by the death of A. F. Melcher, who had contributed much to the science of ground-water hydrology by his studies on permeability and absorption of sedimentary formations for water, oil, and gas. The members of the Committee for 1934 are:

D. G. Thompson, Chairman--United States Geological Survey, Washington, D. C.
Gordon M. Fair--Harvard Engineering School, Cambridge, Massachusetts.

Willard Gardner--Utah State Agricultural College, Logan, Utah.
F. H. Lahee, Dallas, Texas
M. R. Lewis--Oregon State Agricultural Experiment Station, Corvallis, Oregon.
O. E. Meinzer, United States Geological Survey, Washington, D. C.
Morris Muskat--Gulf Research and Development Corp., 327 Craft Ave., Pittsburgh, Pa.
Arthur M. Piper--P. O. Box 217, Lodi, California.
C. S. Slichter, University of Wisconsin, Madison, Wisconsin.
Parker D. Trask, United States Geological Survey, Washington, D. C.

Because of the pressure of other work during the past year your Chairman has not been able to give to the work of the Committee the time that he had hoped to, and no definite action has been taken in regard to certain matters mentioned in last year's report (Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, pp. 366-379). These remain for consideration during the coming year. The present report accordingly is largely a review of current investigations in progress, based upon statements furnished by other members of the Committee and other sources. Four papers relating to underground-water presented at the meeting of the Section are in part due to solicitation by the Committee.

Review of current investigations

Professor Gordon M. Fair reports that he is continuing to investigate, in the laboratory of the Harvard Engineering School, the hydraulic properties of sands. A preliminary report on these studies has been published [see articles listed as 9 and 10 in the bibliography of attached Appendix C] and it is hoped that a more complete report will be published during the present year.

M. R. Lewis [17] of the United States Bureau of Agricultural Engineering, cooperating with the Oregon State Agricultural Experiment Station, and Dr. Willard Gardner and assistants [12], at the Utah State Agricultural College and Experiment Station, have continued mathematical studies of the hydraulics of wells in connection with problems of pumping for irrigation and drainage of irrigated lands.

Dr. Morris Muskat reports several papers by himself and colleagues on problems relating to the flow of homogeneous fluids through sands, especially in connection with ground-water in oil-fields and the mechanics of water-flooding systems [14, 24, 25, 42, and 43]. In one of these papers the authors define a permeability-unit and propose to name it the "darcy," in view of Darcy's fundamental work in establishing laws of flow for porous media. Dr. Muskat also reports that the eastern division of the American Petroleum Institute's Committee on Development and Production Research has considered the question of units and names for permeability of porous media, and also questions of technique in determining permeability. Dr. Meinzer has submitted a statement in regard to this matter, which is attached herewith as Appendix A.

Interest in studies of ground-water in relation to the occurrence and production of petroleum is attested by several other articles published during the year [3, 7, 22, 29, 30, 33, and 41]. In this connection attention may be called to a recently issued book by Dr. Parker D. Trask, "The origin and environment of source sediments of petroleum," which includes a discussion of the texture of sediments and movement of water in them. Mention may also be made of a paper read by O. E. Meinzer at the Dallas meeting of the American Association of Petroleum Geologists under the title "Movements of underground-water," which discusses principles governing the occurrence of ground-water that are of interest to petroleum geologists and engineers. This paper is to be published in the Bulletin of the American Association of Petroleum Geologists.

The Division of Ground-Water of the United States Geological Survey has in progress about 60 projects, many of them in cooperation with State, county, or municipal organizations. Several investigations have been financed by funds allotted to the Geological Survey by the Public Works Administration. Many of these investigations involve a study of special problems of ground-water hydrology, which are yielding valuable field-data in regard to principles. Many of these problems have been described in previous reports of the Committee. Several reports published during the year are listed in the bibliography of attached Appendix C, and brief mention may be made of certain problems still under investigation.

The work of L. K. Wenzel in making extensive pumping tests in Nebraska, in cooperation with the Nebraska Conservation and Survey Division, to study Thiem's method of determining permeability in the field and also using this method to determine the specific yield of the water-bearing materials, has been reported at previous meetings of the Section of Hydrology. During the summer of 1933, using this method with modifications resulting from his earlier work, Mr. Wenzel made pumping tests in two additional localities with good results. The report on this study is now completed and awaiting publication by the United States Geological Survey.

In the Hydrologic Laboratory of the Geological Survey, V. C. Fishel, under the direction of O. E. Meinzer, has been making determinations of permeability with low gradients. A statement of the results of this work is submitted at the present meeting.

In investigations in the vicinity of Salt Lake City and in Ogden Valley, Utah, R. M. Leggette and G. H. Taylor have obtained additional valuable information in regard to transmission of artesian pressure, some of which is given in a paper at the meeting in April 1934 of the Section of Hydrology. During a series of earthquake shocks in Hansel Valley, north of Great Salt Lake, on March 12, 1934, the shocks were strikingly recorded by both pressure-gages and float-recorders on observation-wells in Ogden Valley, about 60 miles distant. A paper by Leggette and Taylor describing the unusual results was presented at the New York meeting of the Eastern Section of the Seismological Society of America, April 30 and May 1, 1934.

Interest continues to grow in regard to observations on fluctuations of the ground-water level, particularly for any relation that may be shown between the groundwater and flow of streams. One paper on this subject by L. L. Harrold was given at the meeting of the Section of Hydrology in April 1934. Another paper, by S. W. Lohman, presented at a meeting of the Hydraulic Power Committee of the Pennsylvania Electric Association on April 25, 1934, describes some of the results of water-table observations that have now been carried on for two years in Pennsylvania, in cooperation with the Pennsylvania Topographic and Geologic Survey. C. F. Merriam and H. W. Lowy, of the Pennsylvania Water and Power Company, have studied the fluctuations of several of these wells in relation to the flow of the Susquehanna River. In connection with studies of soil-erosion by the recently created Soil Erosion Service and studies in the Mississippi Valley by the Mississippi River Committee, plans are also being made for studies by the United States Geological Survey of the fluctuation of water-level in wells in relation to precipitation and runoff. Professor Howard E. Simpson has recently been appointed by Secretary Ickes to make a study for the Mississippi Valley Committee of the Public Works Administration of ground-water fluctuations in several states in the Red River and middle Missouri River basins, especially in reference to the apparent recessions of the ground-water level in recent years. In view of the increasing interest in observations on fluctuations of water-level, a statement by Dr. Meinzer suggesting that the Committee on Underground-Water undertake a survey of agencies now making such observations is timely and is submitted as Appendix B of this report.

C. V. Theis is in charge of a project to study the ground-water conditions of the High Plains province. The project includes a study of the geologic section with collection of numerous samples from outcrops for tests of permeability, measurements of spring-discharge, and the preparation of a contour-map of the erosion-surface of the older rocks upon which rest the Tertiary beds that constitute an important water-bearing formation.

V. T. Stringfield and F. C. Westendick are making an extensive survey of the Peninsula of Florida to obtain data to prepare a contour-map of the water-table and piezometric surface of the principal water-bearing formations. This should yield valuable information as to the source and direction of flow of water in these formations, which is fundamental in studies of the quantity of water and salt contamination in areas of the Peninsula. A recently published report by Mr. Stringfield [37] describes the results of work in an area in Florida in which a deep-well current-meter was used to determine the exact depth at which water was entering deep wells in rock that were uncased for most of their depth. It was found that most of the water was coming from formations other than those that were generally supposed to constitute the principal water-bearing formations, and that there could be a considerable saving by finishing wells at a considerably less depth than formerly. Although the use of the deep-well current-meter to detect leakage has incidentally revealed points where water was entering cased wells, it is believed that this is the first time the meter has been used in uncased wells for the specific purpose of determining the source of the water.

Studies of the relation between fresh ground-water and salt water are in progress in Texas by S. F. Turner and Margaret D. Foster, in part reported to the meeting of the Section of Hydrology in April 1934; in the Atlantic City Region, New Jersey, by H. C. Barksdale, R. W. Sundstrom, and W. L. Lamar, with the cooperation of Maurice S. Brunstein of the Atlantic City Water Department; and on Long Island, New York, by David G. Thompson, Francis G. Wells, Kyle Forrest, and W. L. Lamar. The New York City Department of Water Supply, Gas, and Electricity is also undertaking a rather detailed study of the contamination of fresh-water-bearing strata in the western part of Long Island.

An intensive study of the geology and hydrology of the Warm Springs Area in Georgia is being made by D. F. Hewett, G. W. Crickmay, and W. L. Lamar. Of interest in this connection is a report on thermal springs in the United States, which was undertaken some years ago by Drs. Norah D. and Harold T. Stearns. The report is a compilation of published data, with much additional information furnished by field men of the United States Geological Survey, the Forest Service, the National Park Service, and the Indian Service. The study was necessarily laid aside for other work, but it is now being brought up to date and prepared for publication by G. A. Waring.

In addition to the more or less usual ground-water studies in progress, several projects relating to ground-water supplies are being carried on as emergency relief projects or as special projects financed from allotments made by the Public Works Administration. In Ohio, for example, the State Water Conservation Board, in cooperation with the State geologist, has undertaken an extensive survey of ground-water supplies of the entire State, employing two men in each county, or a total of about 175 men. An early report on this project indicates that data had been already obtained in regard to about 75,000 wells, and it was expected that by the end of April 1934 the data would cover about 225,000 wells. Another project in Ohio provides for the sealing of many abandoned coal mines, primarily to reduce the impairment of water supplies by acid water wasting from the mines. Although the results of this work will probably not be apparent immediately, it will be interesting to observe future changes in chemical character and rate of discharge of the ground-waters issuing from these mines. In Monroe County, New York, the County Planning Board, with R. M. Leggette of the Geological Survey acting in an advisory capacity, has employed several men on a relief basis to make a very detailed survey of wells, particularly to discover the presence of buried preglacial channels in the bedrock which may yield large supplies.

A Public Works project, under the direction of H. I. Smith of the Conservation Branch of the United States Geological Survey, provides for the prevention of ground-water flow into lead and zinc mines in Oklahoma. G. F. Loughlin has recently made a study of the deep ground-water conditions together with deep-ore resources in the Cripple Creek, Colorado, mining district to determine the justification for a new deep-drainage tunnel that would be driven as a Public Works project.

The Division of Water Resources of the California Department of Public Works has continued extensive studies of various ground-water problems in the State. Some of these studies are described in the report of the Committee on Absorption and Transpiration. A recently issued report on the Santa Clara Valley by Everett N. Bryan [4] contains data in regard to marked lowering of water-levels resulting from heavy pumping for irrigation (an average of five feet a year since 1915), the decrease in ground-water storage, and natural and artificial replenishment of the ground-water reservoir [4]. An article by Howard S. Rappleye [31] in the Engineering News-Record for June 29, 1933, described the results of releveling by the Coast and Geodetic Survey, which revealed a subsidence of the land in the vicinity of San Jose, in Santa Clara Valley, which ranged from a fraction of a foot to as much as four feet. A letter from Fred H. Tibbets in the Engineering News-Record for August 17, 1933, suggested that this subsidence may be due to a lowering of the water-level as a result of heavy pumping from wells. It is understood that further studies of this problem are to be made, with releveling of certain stretches at frequent intervals.

A report by C. S. Scofield [34] on the quality of irrigation waters in the south coastal-basin area of California, although properly coming within the purview of the Committee on Chemistry of Natural Waters, may be mentioned here because it includes analytical data in regard to more than 3200 samples of ground-water from 1433 well locations. It also presents data in regard to the problem of contamination of fresh-water-bearing strata by salt water from the ocean, with a discussion of criteria to distinguish between contamination from the ocean and contamination from formations bearing salt water in oil-fields.

Physical and legal control of the use of ground-water to prevent overdraft on the water-bearing formations has been discussed in a paper by O. E. Meinzer on "Progress in the control of artesian water supplies," presented before the Society of Economic Geologists at Princeton in July, 1933 [21]. In connection with this subject, attention may be called to a law passed by the New York Legislature at its session of 1933 providing that "no person, firm, or corporation shall hereafter install or operate any new or additional wells in the counties of Kings, Queens, Nassau, and Suffolk [that is, all of Long Island] to withdraw water from underground sources for manufacturing or industrial purposes or for use in manufacture or industry where the capacity of any such well or wells singly or in the aggregate is in excess of 100,000 gallons a day, without first obtaining the approval of the [State Water Power and Control] Commission." The law refers to the fact that information presented by the Water Power and Control Commission and the United States Geological Survey indicates depletion of the ground-water supplies beneath certain parts of the island (with danger of salt-water contamination) and states that "this enactment is made in the exercise of the police power of the State, and its purposes generally are to protect the public health and public welfare in conserving the supply of water for domestic consumption." This law is believed to be a significant departure from previous practice in the control of use of ground-water, in that it invokes the police power of the State to protect over-development of ground-water supplies, which for a large population constitute the sole source of water for domestic use.

Appended to this report is a list of papers relating to ground-water hydrology that have been published during the year. They have been selected from a much larger list for which abstracts have been prepared by members of the Division of Ground-Water of the United States Geological Survey, under the direction of A. N. Sayre, for publication in the Annotated Bibliography of Economic Geology and certain foreign geological abstract magazines.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--PERMEABILITY

O. E. Meinzer

In the paper entitled "The measurement of the permeability of porous media for homogeneous fluids" by R. D. Wyckoff and others [42] a unit of permeability is proposed which is based on centimeters, seconds, and atmospheres of pressure (76 centimeters of mercury).

In 1923, when the Hydrologic Laboratory of the United States Geological Survey was organized, much study was given to the question of a coefficient of permeability, and a coefficient was adopted which is based on feet and gallons a day (U. S. Geol. Survey Water-Supply Paper 596, p. 148). This coefficient has been extensively used and has proved very satisfactory in ground-water work. It has the merit of being readily applicable to field-conditions. It is, moreover, of convenient size, the coefficients of most water-bearing materials being integers of two or three figures, that is, between 10 and 1000. It was adopted in place of Slichter's "transmission-constant" (U. S. Geol. Survey Water-Supply Paper 67, p. 27, 1902), after much careful consideration, largely because the "transmission-constant" of most water-bearing materials is inconvenient in being only a small decimal.

It is probably desirable to have a coefficient expressed in C. G. S. units as well as one expressed in feet, gallons, and days, with a recognized conversion-factor. However, the suitability of the coefficient suggested in the paper above cited is open to question, and the whole subject ought to receive careful consideration by all who are interested in permeability with a view to developing one C. G. S. or so-called absolute expression that will be recognized by all. The following objections to the Wyckoff expression are at least worthy of consideration:

(1) There appears to be no good reason for expressing the hydraulic gradient in atmospheres per centimeter, that is, as a column of 76 centimeters of mercury per centimeter. In 1929 a coefficient of permeability was given by P. G. Nutting for expressing the results obtained with oil-sands in the Physical Laboratory of the United States Geological Survey (Some physical problems in oil-recovery, Oil and Gas J., November 21, 1929). He states, "These permeabilities may be reduced to absolute units (cc/sec/cm^2 per megadyne/cm^2/cm)." The expression for hydraulic gradient given by Nutting appears to be more nearly "absolute" than that proposed by Wyckoff. However, it would seem that consideration might also be given to a coefficient in which the hydraulic gradient is expressed as a head of one centimeter of water per centimeter of percolation-distance, that is, for water merely a gradient of unity, or 100 per cent.

(2) Permeability is a quality possessed by a porous material and can properly be expressed by a physical coefficient indicating the degree of that quality. It would seem to be the best usage not to apply the name "darcy" or any other name to an expression of this kind.

(3) Both the Wyckoff and the Nutting expressions have the unsatisfactory feature of Slichter's transmission-constant in giving units so large that the permeability of the ordinary water-bearing materials must be stated in small decimals. Hasty computations by V. C. Fishel give the following equation:

1 Nutting unit = 1.128 "darcys" = 1196 C. G. S. units
with hydraulic gradient of 100 per cent for water =
25,338,300 coefficients of permeability used in the
Hydrologic Laboratory.

A very useful and timely activity for the Committee on Underground-Water during the ensuing year, which has been especially suggested to me by Dr. Muskat's statement regarding the activity of the eastern division of the American Petroleum Institute Committee referred to in the Chairman's report, would be to establish contact with all agencies that are concerned with permeability, to make a survey of methods of work that have been used, results that have been obtained, and coefficients or units that have been adopted for expressing the results, and further to promote cooperation in obtaining standardization in methods of work and expression.

U. S. Geological Survey,
Washington, D. C.

APPENDIX B--LAKE AND GROUND-WATER LEVELS

O. E. Meinzer

An outstanding achievement of the Section of Hydrology has been the work of the Committee on Glaciers in assembling the existing records of the advance and retreat of the glaciers in the Western States and in Alaska, encouraging various agencies in making periodic observations, systematizing and standardizing the work, and providing for the compilation and preservation of the data obtained from year to year.

The fluctuation of lake levels is a closely related subject that is equally fundamental in the study of hydrology. In 1922 I published a map giving the distribution of 68 Pleistocene lakes in the Basin and Range province and showed that the desiccation of these lakes could have been caused by change in temperature as well as change in precipitation (Geol. Soc. Amer. Bull., v. 33, pp. 541-552, 1922). Abundant and convincing evidences of changes in climate in the Pleistocene epoch or at its end are afforded both by the ancient drift-sheets and by the ancient lake features, but the question as to the relative importance of changes in temperature and changes in precipitation is still very obscure.

The United States Weather Bureau has for many years systematically obtained and published records of temperatures and precipitation, and the Water-Resources Branch of the United States Geological Survey has rendered a similar service in regard to runoff. Observations of fluctuations of the stage of lakes, large and small, in different parts of the country have been made by the United States Lake Survey and other Federal bureaus and by states and others. Better organization is needed, however, to obtain and preserve adequate records of current fluctuations in all lakes. I recommend, therefore, that during the ensuing year the Committee on Evaporation make a survey of the lake records already available and the agencies that are at present making observations, and that it consider either the feasibility of undertaking a task with respect to lake levels comparable to that of the Committee on Glaciers or an alternative plan for having this work done by some other agency. For this purpose it will doubtless be desirable to enlarge the Committee on Evaporation or perhaps to create a sub-committee.

Precipitation is at the beginning of the hydrologic cycle, whereas evaporation (which varies with temperature) and runoff are at the end of the cycle. Between these there is storage of several kinds, chiefly as snow and ice, and water in lakes, soil, and the zone of saturation--immediately below the water-table and in the artesian reservoirs. Water-levels in wells fluctuate continuously as a result of variations in precipitation and evaporation, and these fluctuations produce variations in spring-flow and therefore in runoff. The United States Geological Survey is making periodic measurements on about 3000 observation wells and is maintaining automatic water-stage recorders on about 120 wells. Many measurements of water-levels are also being made by the State Engineer of California and numerous other agencies. Most of the measurements by the Geological Survey and other agencies, however, are made in areas of heavy withdrawals and therefore do not represent natural conditions. Most of the records cover only short periods, and there is great lack of standardization in obtaining and recording the data and in publishing or otherwise preserving the records. This subject is very much larger and more complex than that pertaining to glaciers or lakes, and it is doubtful whether it could be adequately handled by any committee composed of volunteer workers. However, it should be possible to make a survey of the existing records and the work that is being done and to prepare recommendations for future work and for the standardization of methods. I recommend that in the ensuing year this task be undertaken by the Committee on Underground-Water with the cooperation of the Committee on Absorption and Transpiration.

U. S. Geological Survey,
Washington, D. C.

APPENDIX C--A SELECTED LIST OF PAPERS RELATING TO GROUND-WATER HYDROLOGY

A. N. Sayre

In the following list brief statements have been added to certain references to call attention to special phases of ground-water problems which are not apparent from the titles. Abstracts of most of these papers have been or will be published in the Annotated Bibliography of Economic Geology.

[1] J. T. Auten, Porosity and water absorption of forest soil, J. Agric. Research, v. 46, No. 11, pp. 997-1014, 1933.

[2] C. S. Boruff and G. B. Abbott, Determination of fluorides in Illinois waters, Ind. and Eng. Chemistry Anal. ed., v. 5, pp. 236-238, 1933.

[3] H. R. Brankstone, W. B. Gealy, and W. O. Smith, Improved technique for determination of densities and porosities, Amer. Assoc. Petroleum Geologists Bull., v. 16, No. 9, pp. 915-923, 1932.

[4] E. N. Bryan, Santa Clara investigation, California Div. Water-Resources Bull. 42, 1933.

[5] R. C. Cady, Preliminary report on ground-water resources of northern Virginia, Virginia Geol. Survey Bull. 41, 48 pp., 1933.

[6] California Department of Public Works, Division of Water Resources, South Coastal Basin Investigation, Records of ground-water levels at wells, California Div. Water-Resources Bull. 39, 590 pp., 9 maps (8 in pocket), Sacramento, 1932.

[7] L. C. Case, Base-replacement studies of Oklahoma shales--Critique of Taylor hypothesis, Amer. Assoc. Petroleum Geologists Bull., v. 17, No. 1, pp. 66-79, 1933.

[8] L. M. Clarkson, Safety of water supplies, Southeastern Section, Amer. Water Works Assoc. J., v. 3, No. 1, pp. 62-68, 1933.

[9] G. M. Fair, Flow of water through sand, Civ. Eng., v. 4, p. 137, 1934.

[10] G. M. Fair and L. P. Hatch, Fundamental factors governing the stream-line flow of water through sand, Amer. Water Works Assoc. J., v. 25, No. 11, pp. 1551-1563, with discussion by Herbert E. Hudson, pp. 1563-1565, 1933.

[11] G. H. Fancher and J. A. Lewis, A note on the flow of fluids through porous media, Science, v. 75, No. 1948, p. 468, 1932.

[12] Doris Farr and Willard Gardner, Problems in the design of structures for controlling ground-water, Agric. Eng., v. 14, No. 12, pp. 349-352, 1933.

[13] A. G. Fiedler and S. S. Nye, Geology and ground-water resources of the Roswell artesian basin, New Mexico, U. S. Geol. Sur. Water-Supply Paper 639, 1933. [A quantitative study of an area that includes some of the largest flowing wells in the United States. Describes use of deep-well current-meter to discover leakage from wells. Discusses legal control of use of ground-water to prevent overdraft.]

[14] William Hurst, Unsteady flow of fluids in oil-reservoirs, Physics, v. 5, pp. 20-30, 1934.

[15] W. D. Johnston, Jr., Ground-water in the Paleozoic rocks of northern Alabama, Ala. Geol. Sur. Spec. Rep. 16, 414 pp. and tables, 1933. [Gives special attention to the occurrence of water in cavernous limestones and the formation of caves.]

[16] J. B. Knaebel, Mining practices at the Edwards Mine of the St. Joseph Lead Company, St. Lawrence County, New York, U. S. Bur. Mines Information Circ. 6586, February, 1932. [Gives data in regard to quantity of water in mine.]

[17] M. R. Lewis, The economic design of wells and pumping plants, Agric. Eng., v. 14, No. 11, pp. 312-315, 1933.

[18] O. E. Meinzer, History and development of ground-water hydrology, J. Acad. Sci., Washington, v. 24, No. 1, pp. 6-31, 1934.

[19] O. E. Meinzer, Movements of underground-water (paper read at meeting of Amer. Assoc. Petroleum Geologists at Dallas, March, 1934; to be published in Assoc. Bull.).

[20] O. E. Meinzer, Notable improvements in ground-water development, Eng. News-Record, v. 110, pp. 750-752, June 8, 1933.

[21] O. E. Meinzer, Progress in the control of artesian water supplies (to be published in a forthcoming issue of Eng. News-Record).

[22] T. V. Moore and others, The determination of permeability from field data, Amer. Petroleum Inst., v. 14M, No. 4, pp. 4-13, 1933.

[23] R. G. Moss, Preliminary report on ground-water resources of the shallow-water basin in Scott and Finney Counties, Kansas, Kans. Geol. Sur. Circ. 5, 7 pp. (typescript), October 1, 1933.

[24] Morris Muskat, The flow of compressible fluids through porous media and some problems in heat conduction, Physics, v. 5, pp. 71-94, 1934.

[25] Morris Muskat and R. D. Wyckoff, A theoretical analysis of water-flooding networks, Amer. Inst. Min. and Met. Eng. Tech. Pub. 507, Petroleum Division, 1933.

[26] E. S. Perry, Artesian wells as a source of water for municipal supply at Fort Benton, Montana, Mont. Bur. Mines and Geology, Misc. Contr. 4 (mimeographed), 7 pp., illus., December, 1932.

[27] E. S. Perry, Ground-water resources of Judith Basin, Montana, Mont. Bur. Mines and Geology Mem. 7, 30 pp., illus., December, 1932.

[28] A. M. Piper, Ground-water in southwestern Pennsylvania, Penn. Top. and Geol. Sur., 4th ser., Bull. W1, 406 pp., map, 1933.

[29] F. B. Plummer, E. C. Sargent, and R. B. Newcombe, Thermal gradients and chemical composition of underground-waters in altered volcanic rocks of the Balcones fault-zone in central Texas (abstract of paper to be offered at 46th annual meeting), Geol. Soc. Amer. Bull. 13, 1933.

[30] W. W. Porter, II, Influence of speed of migration of oil on water-encroachment at Casmalia, California, Amer. Assoc. Petroleum Geologists, v. 17, pp. 1133-1136, 1933.

[31] H. S. Rappleye, Recent areal subsidence found in releveling, Eng. News-Record, v. 110, p. 845, June 29, 1933. [Letter from Fred H. Tibbets in Eng. News-Record, v. 111, p. 204, August 17, 1933, suggests that this subsidence is due to a lowering of the ground-water level as a result of heavy pumping for irrigation.]

[32] J. O. Riddel, Excluding salt water from island wells--a theory of the occurrence of ground-water based on experience at Nassau, Bahama Islands, Civ. Eng., v. 3, No. 7, pp. 383-385, 1933. Discussion of this paper by David G. Thompson in Civ. Eng., v. 3, No. 10, pp. 579-580, 1933.

[33] W. L. Russell, Subsurface concentration of chloride brines, Amer. Assoc. Petroleum Geologists Bull., v. 17, No. 10, pp. 1213-1228, 1933.

[34] C. S. Scofield, South Coastal Basin investigation--quality of irrigation waters, Calif. Div. Water Resources Bull. 40, 1933.

[35] W. O. Smith, Capillary flow through an ideal uniform soil, Physics, v. 3, No. 3, pp. 139-146, 1933.

[36] W. O. Smith, The final distribution of retained liquid in an ideal uniform soil, Physics, v. 4, pp. 425-438, 1933.

[37] V. T. Stringfield, Exploration of artesian wells in Sarasota County, Florida, Fla. Geol. Sur. 23d-24th Ann. Rep., 1930-32, pp. 195-227, 1933.

[38] V. T. Stringfield, Ground-water resources of Sarasota County, Florida, Fla. Geol. Sur. 23d-24th Ann. Rep., 1930-32, pp. 121-194, 1933. [A study of the quantity of water available for irrigation. Discusses problem of contamination of fresh ground-water by salt water.]

[39] W. O. Smith, P. D. Foote, and P. F. Busang, Capillary retention of liquids in assemblages of homogeneous spheres, Phys. Rev., v. 36, No. 3, pp. 524-530, 1930.

[40] F. G. Wells, Ground-water resources of western Tennessee, U. S. Geol. Sur. Water-Supply Paper 656, 311 pp., 1933 (in cooperation with Tennessee Geol. Survey). [Includes a quantitative study of the ground-water supply available for the city of Memphis.]

[41] H. D. Wilde, Jr., and F. H. Lahee, Some principles of efficient oil-field development, Amer. Assoc. Petroleum Geologists Bull., v. 17, No. 8, pp. 981-1002, 1933.

[42] R. D. Wyckoff, H. G. Botset, Morris Muskat, and D. W. Reed, Measurement of permeability of porous media, Amer. Assoc. Petroleum Geologists Bull., v. 18, pp. 161-190, 1934. [A summary of this paper under the title "The measurement of the permeability of porous media for homogeneous fluids" appears in Rev. Sci. Instr., v. 4, pp. 394-405, 1933.

[43] R. D. Wyckoff, H. G. Botset, and Morris Muskat, The mechanics of porous flow applied to water-flooding problems, Amer. Inst. Min. Met. Eng. Trans., v. 103, pp. 219-249, 1933.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON DYNAMICS OF STREAMS, 1933-34

Lorenz G. Straub, Chairman

With the work of the previous year as a basis the Committee on Dynamics of Streams during the year 1933-34 has distributed certain phases of its activities among different groups of members in order that a more concentrated effort might be given to the subject-matter with which the Committee is concerned.

In order to avoid the provincialism which sometimes occurs in the development of a science it appeared obvious that a means of propagation of the results of current reports was definitely a continuous function of the Committee. Likewise the standardization of the terminology required for discussion of stream dynamic problems seemed to be a definite and important phase of the prospective activities.

In the course of time some problems of the broad field with which the Committee is concerned will prove more important than others; not all of them can be advantageously emphasized at the same time. For example, although considerable attention has been given to the transportation of sediment in open channels, up to the last year a neglected subject was that of the dynamic action of rain in surface runoff and soil-erosion.

With the foregoing considerations in view, the Committee on Dynamics of Streams formed three sub-committees, not as permanent rigorously defined groups, but rather as divisions concerned particularly with certain special activities in addition to those of the Committee as a whole. The complete membership of the Committee is as follows:

Lorenz G. Straub, Chairman--University of Minnesota, Minneapolis, Minnesota.
K. H. Beij--National Bureau of Standards, Washington, D. C. (B)

H. H. Bennett--Soil-Erosion Service, Interior Department, Washington, D. C. (E, Chairman)
R. W. Davenport--United States Geological Survey, Washington, D. C. (N)
J. B. Drisko--Bureau of Reclamation, Denver, Colorado. (B)
H. M. Eakin--Mississippi River Commission, Vicksburg, Mississippi. (B)
H. V. Geib--Blackland Experiment Station, Temple, Texas. (E)
C. S. Howard--United States Geological Survey, Washington, D. C. (E)
E. W. Lane--United States Bureau of Reclamation, Denver, Colorado. (B)
L. M. Lawson--627 First National Bank Building, El Paso, Texas. (E)
W. C. Lowdermilk--Soil-Erosion Service, Department of the Interior, Washington, D. C. (E)
Gerard H. Matthes--Box 665, Vicksburg, Mississippi. (N, Chairman)
George W. Musgrave--Erosion Station, Clarinda, Iowa. (E)
Martin E. Nelson--United States Engineer Office, Engineering Building, Iowa City, Iowa. (B)
Morrough P. O'Brien--University of California, Berkeley, California. (B, Chairman)
R. L. Parshall--United States Bureau of Agricultural Engineering, Fort Collins, Colorado. (B)
G. W. Pickels--University of Illinois, Urbana, Illinois. (N)
C. E. Ramser--Red Plains Erosion Station, Guthrie, Oklahoma. (E)
Wm. W. Rubey--United States Geological Survey, Washington, D. C. (N)
F. C. Scobey--Room 219, Post-Office Building, Berkeley, California. (B)
Roy N. Towl--400 City Hall, Omaha, Nebraska. (B)
Arthur C. Trowbridge--University of Iowa, Iowa City, Iowa. (B)
Herbert D. Vogel--United States Waterways Experiment Station, Vicksburg, Mississippi. (N)
H. H. Wheaton--State College, Fresno, California. (B)
N. E. Winters--State Agricultural College, Stillwater, Oklahoma (E)
[Note: The designations (B), (E), and (N) indicate membership on the Sub-Committees on Bibliography, Surface Runoff and Soil-Erosion, and Nomenclature, respectively.]

As will be noted, the membership of the Committee was increased, several outstanding investigators having been elected to provide a better balanced organization. The new members are H. V. Geib, W. C. Lowdermilk, George W. Musgrave, C. E. Ramser, H. H. Wheaton, and N. E. Winters.

The organizations of the sub-committees are as follows: Sub-Committee on Bibliography--O'Brien, Chairman; Beij, Drisko, Eakin, Lane, Nelson, Parshall, Scobey, Towl, Trowbridge, and Wheaton. Sub-Committee on Nomenclature--Gerard H. Matthes, Chairman; Davenport, Lane, Pickels, Rubey, and Vogel. Sub-Committee on Dynamic Action of Rain in Surface Runoff and Soil-Erosion--Bennett, Chairman; Geib, Howard, Lawson, Lowdermilk, Musgrave, Ramser, and Winters.

The Sub-Committee on Bibliography has undertaken as a major function the review of current literature, both American and foreign, on subjects related to the dynamics of streams. The Military Engineer, Journal of the Society of American Military Engineers, which devotes much of its space to river hydraulics articles, has agreed to cooperate with the Committee in publishing the reviews and in providing reprints for circulation among those interested in stream dynamics.

Considerable progress is being made by the Sub-Committee on Nomenclature in the codification of various reports on river hydraulics terminology. It is hoped to present a glossary of terms at the next annual meeting.

The activity of the Sub-Committee on Surface Runoff and Soil-Erosion is expressed by the symposium of papers on erosion presented at the meeting of the Section of Hydrology in April 1934.

Among its other activities the Committee on Dynamics of Streams has fostered the preparation of thirteen of the papers presented at the fifteenth annual meeting of the American Geophysical Union.

University of Minnesota,
Minneapolis, Minnesota

APPENDIX A--REPORT OF SUB-COMMITTEE ON NOMENCLATURE

Gerard H. Matthes, Chairman

The Sub-Committee on Nomenclature was organized in July 1933, the membership being given in the report of the Committee on Dynamics of Streams.

First to come before the attention of the Sub-Committee was a brief terminology prepared by Lieutenant Vogel for use at the United States Waterways Experiment Station. The work at this Station is intimately concerned with dynamics of streams in practically all its phases, and all of the terms submitted by Lieutenant Vogel are of immediate interest.

It was found that a great deal has been accomplished by other organizations in the way of attempts at standardizing hydraulic terms. Accordingly, the attention of the Sub-Committee was next invited to a consideration of available glossaries containing terms that come within its province. This includes the following: (a) "American tentative standard symbols for hydraulics" prepared by the Sectional Committee on Scientific and Engineering Symbols and Abbreviations of the American Standards Association, dated July 1929; (b) "Standard symbols and glossary for hydraulics and irrigation" compiled by the Special Committee on Irrigation Hydraulics of the American Society of Civil Engineers, published in Proceedings for May 1932; and (c) final revised edition of (b), received in mimeograph form the latter part of December 1933.

These glossaries and lists of symbols cover, in part, much of the ground which this Sub-Committee set out to cover. Since these represent a great deal of labor on the part of hydraulicians of recognised ability, it is evident that the Sub-Committee will greatly benefit thereby and may likely find its task greatly shortened. It is hoped to bring the work of the Sub-Committee to conclusion during the present year.

The Sub-Committee earnestly requests the cooperation of all members of the Section of Hydrology interested in devising terminology and definitions relating to dynamics of streams, and shall appreciate having brought to its attention any word or expression or the lack of a suitable word or expression requiring its attention.

Mississippi River Commission,
Vicksburg, Mississippi

REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1933-34

C. S. Howard, Chairman

The personnel of this Committee during the past year, practically the same as during the previous year, has been as follows:

C. S. Howard, Chairman--United States Geological Survey, Washington, D. C.
L. C. Case--Gypsy Oil Company, Tulsa, Oklahoma.
W. D. Collins--United States Geological Survey, Washington, D. C.
H. F. Flynn--United States Engineer Office, 35 South Ninth Street, Philadelphia, Pennsylvania.
W. P. Kelley--University of California, Riverside, California.
Alfred C. Lane--Tufts College, Tufts College, Massachusetts.
Augustus Locke--477 Mills Building, San Francisco, California.
R. D. Leitch--United States Bureau of Mines, Pittsburgh, Pennsylvania.
H. T. Logan--United States Bureau of Standards, Washington, D. C.
Thomas S. Lovering--United States Geological Survey, Washington, D. C.
Thomas H. Means--111 Sutter Street, San Francisco, California.
F. B. Plummer--University of Texas, Austin, Texas.
J. W. Sale--United States Food and Drug Administration, Washington, D. C.
C. S. Scofield--Bureau of Plant Industry, Department of Agriculture, Washington, D. C.
Thomas G. Thompson--University of Washington, Seattle, Washington.

Progress is reported in the subjects in which the members of this Committee are interested.

A study of the chemical composition of natural water at its origin was reported by Collins and Williams in a paper published in Industrial and Engineering Chemistry on chloride and sulphate in rainwater. The results obtained in this study indicate that, for the major part of the country, rain or snow contains less than 0.3 part per million of chloride and less than two parts per million of sulphate. These concentrations, especially those for chloride, are much smaller than some of the values reported by previous investigators.

The results of analyses of some surface-waters of California with comparisons for a few of the rivers of the composition after a period of about 20 years, are given in a paper by Love included in Bulletin 29 of the Division of Water Resources of the California Department of Public Works. Extracts from this paper follow:

"The analyses made in 1930 indicate that the concentration of dissolved matter in certain rivers in the Sacramento, San Joaquin, and Santa Ana regions, particularly the Feather, American, Stanislaus, and Santa Ana rivers, was considerably less than found by Van Winkle and Eaton, notwithstanding the fact that the discharge of these rivers was much less than in 1906-08.

"The Yuba, San Gabriel, and Owens rivers and Arroyo Seco near Soledad appeared to have changed very little in concentration, but the Ventura River contained more dissolved matter than at any time in 1908.

"The complete analyses of 71 samples from the Sacramento River at Sacramento in 1931-32 show higher concentration of dissolved solids than in 1906-08 but do not indicate the salt-water encroachment."

These findings on the Sacramento are in accordance with those reported by this Committee in last year's report.

A report by C. S. Scofield on the quality of irrigation-waters in the South Coastal Basin in California was published as Bulletin 40 of the Division of Water Resources of the California Department of Public Works. The following is quoted therefrom: "In general, and particularly in the Coastal Plain, it is found that the subsoil waters, that is, the water in or just below the root-zone, are more concentrated than the deeper waters usually drawn upon by irrigation-wells. It has been found that the waters in deeper strata in the sections close to the ocean in the Coastal Plain are even less saline than the average of the surface-waters now contributed to the Coastal Plain from the upper basins. From this it is inferred that the major portion of the waters now found in these deeper strata reached the Coastal Plain as floods from the high mountain watershed which are known to be of very low salinity and from rainfall on areas where penetration is possible. It has been found also that the intensity of boron-contamination is much greater in some of the strata of the sediments of the San Bernardino Basin than in others. . . . . . Along the ocean-front of the Coastal Plain where the static levels of the underground-water are below sea-level there has been some apprehension of sea-water intrusion. An inquiry involving the study of the quality of the water in 129 wells located in a zone three miles wide along the coast shows that there is some evidence of intrusion in the Venice Area and along San Pedro Bay. It appears that this intrusion has not yet progressed much beyond a mile from the beach in either of these sections and that elsewhere the evidence of intrusion is slight. It seems probable that some of the salinity-contamination found to have occurred farther back from the beach may have been due to oil-well waters rather than ocean-water."

A number of papers on methods of analysis, especially for the analysis of sea-water, prepared during the past year by workers in the Oceanographic Laboratories at the University of Washington are listed below.

Papers published

(1) T. G. Thompson and H. J. Taylor, Determination and occurrence of fluorides in sea-water, Ind. Eng. Chem., Anal. Ed., v. 5, p. 87, 1933.

(2) B. D. Thomas and T. G. Thompson, Lithium in sea-water, Science, v. 77, pp. 547-548, 1933.

(3) R. J. Robinson and H. E. Wirth, Photometric investigations of Nessler reaction and Witting method for determination of ammonia in sea-water, Ind. Eng. Chem., Anal. Ed., v. 5, p. 417, 1933.

(4) T. G. Thompson and H. G. Houlton, Determination of silicon in sea-water, Ind. Eng. Chem., Anal. Ed., v. 5, p. 417, 1933.

Papers accepted for publication

(1) B. D. Thomas, T. G. Thompson, and C. L. Utterback, Electrical conductivity of sea-water, J. Conseil Internat. Explor. Mer.
(2) C. L. Utterback, T. G. Thompson, and B. D. Thomas, Refractivity-chlorinity relations, J. Conseil Internat. Explor. Mer.
(3) T. G. Thompson, B. D. Thomas, and C. A. Barnes, Distribution of dissolved oxygen in the North Pacific, Chapter in James Johnstone Memorial Volume, Liverpool, England.
(4) R. J. Robinson and T. G. Thompson, The waters of the Puget Sound Region, Proc. Fifth Pacific Sci. Cong.
(5) N. M. Carter, E. G. Moberg, T. Skogsberg, and T. G. Thompson, Reporting of data in oceanographical chemistry, Proc. Fifth Pacific Sci. Cong.
(6) R. Tschudy, Photosynthesis in red algae, Amer. J. Botany.
(7) R. C. Miller, Observations on hydrogen-ion concentration and temperature of surface-waters of several seas, Proc. Fifth Pacific Sci. Cong.
(8) R. J. Robinson and H. E. Wirth, Report on the free ammonia, albuminoid nitrogen, and organic nitrogen in the waters of the Puget Sound Area during the summers of 1931 and 1932, J. Conseil Internat. Explor. Mer.
(9) R. J. Robinson and H. E. Wirth, Free ammonia, albuminoid nitrogen, and organic nitrogen in the waters of the Pacific Ocean off the coast of Washington and Vancouver Island, J. Conseil Internat. Explor. Mer.

The Director of the Oceanographic Laboratories, Dr. T. G. Thompson, attended the Congress of the International Union of Geodesy and Geophysics in Lisbon, Portugal, in September 1933, and later visited a number of marine laboratories in southern Europe.

The work on corrosion of ferrous metals by soils has been carried on by the Bureau of Standards. A brief statement of this work prepared for this Committee report is as follows:

"Corrosion of ferrous materials underground is influenced by both the concentration and composition of the soluble material present in soil waters. In general, it appears that as the concentration of soluble salts in the soil increases the greater is the corrosiveness of the soil. Measurements of the electrical resistivity of soils, which is dependent upon the composition and concentration of salts present, have been successfully employed in locating areas differing in corrosiveness in regions in which soluble salts tend to accumulate in the soil.

"One of the effects of dissolved salts in the soil with respect to corrosion is that with increasing concentration of salts the resistance of the electrical circuits associated with corrosion is reduced. This results in a greater flow of current and consequently a greater loss of metal.

"The rate of corrosion of metal depends very largely upon the character of the products of corrosion, particularly their solubility, permeability, and adherence to the surface of the metal. Lead, for instance, forms an insoluble basic carbonate coating in certain hard waters, but in soft waters high in carbon dioxide, soluble lead salts are formed and the lead corrodes rapidly. Similarly in the case of iron, it has been observed that soils containing calcium carbonate in the absence of appreciable quantities of soluble salts are usually relatively noncorrosive. The presence of calcium carbonate in solution tends to maintain a continuous film of the hydroxides of iron on the metal surface which protects the metal from rapid corrosion. In acid soils this hydroxide film does not form and corrosion results, the rate depending upon the total acidity of the soil. Furthermore, soil-waters high in sodium chloride tend to prevent the formation of the hydroxide film because of the solubility of ferrous hydroxide in solution of sodium chloride.

"In addition to its effect in maintaining a protective film of metal hydroxides, calcium carbonate may in the absence of certain soluble salts be itself deposited upon the metal surface. By restricting the diffusion of oxygen to the cathodic surface, the carbonate film tends further to reduce the rate of corrosion. However, when salts such as sodium chloride are present, the tendency for the carbonate film to form is very much reduced because of the solubility of calcium carbonate in sodium-chloride solutions.

"An investigation of the influence of the concentration and composition of soil-waters is now in progress at the Bureau of Standards. Analyses of water extracts of soils are being made and the data obtained correlated with the results of field and laboratory tests. It is expected that a better understanding of the chemical reactions involved in soil-corrosion will lead to improved methods for identifying corrosive soils and will allow the most suitable material to be specified for any given corrosive condition."

In the study of chemical composition of subsurface-waters in relation to geological environment and related problems, considerable work has been done this year.

At the University of Texas the study has been continued on underground-waters adjacent to the so-called serpentine plugs of the central Texas district by Plummer, Sargent, and Newcombe. Dr. Plummer reports: "Results of our work indicate rather definitely that the waters are not normal for the depth-zones at which they occur where they have migrated upward from a much deeper source and have decidedly different chemical characteristics from normal waters that occur at the depths at which these waters were samples. The analyses also throw some light on the chemistry of the alteration of the serpentine rock and also had an important bearing on the possible origin of the oils that occur in some of the serpentine deposits. We have also carried on a rather detailed survey of some shallow underground-waters in the vicinity of the Greta oil-fields located in South Texas near Corpus Christi. Our special interest was to determine if the presence of large pools of oil at great depths and abnormally high pressures had not affected the chemical constitution of the shallow-waters. This work is now well under way and will be completed this spring."

The study of the chemical composition of waters draining from mines has been continued, this statement being furnished by Mr. R. D. Leich: "Most of my own time during the past year has been spent in furthering the information that sealing abandoned coal mines or worked out sections of active mines in some manner so as to permit natural drainage to flow therefrom and yet prevent air-circulation or frequent interchange, will result in changing acid to alkaline waters. This takes place by preventing continued oxidation of pyrite, which in some cases is only assured by flooding most or all of the underground areas mined out, with water. Besides preventing continued oxidation, this usually results in raising the underground-water level, sometimes to its original normal. Natural springs and other sources are often thus restored and water which would otherwise percolate through strata above the coal and then reappear in an acid condition can no longer enter the mined out area. Note, however, that this is only one method of preventing continued oxidation and that the main one consists in constructing water trap stoppings in the drainage entries and tightly closing others in some manner."

The report of a study on salt-water encroachment in the Galveston area, Texas, was presented before the Section of Hydrology during annual meetings in April 1934 by S. F. Turner and Margaret D. Foster.

A report of some work done by Dr. Schlundt and by W. R. Bennett on the radioactivity of the Yellowstone Springs was made by Dr. Lane to the Section of Geodesy, April 26, 1934.

U. S. Geological Survey,
  Washington, D. C.

PAPERS

Washington, D. C., April 26, 27, and 28, 1934

EVAPORATION AT HIGH ALTITUDES AND LATITUDES

J. E. Church

Foreword--The writer is under special obligations to Robert E. Horton for causing the resurrection of the data upon which the following paper is based and to Francois E. Matthes for pointing out their application to glacier-evolution at mountain tops. Walter J. Herz deserves special commendation for serving as pinch computer in preparing the tables.

This study of evaporation begun in 1910 represents not so much a finished piece of work entered upon with the refinement of laboratory method as a pioneer effort based upon scant material and observers. Its value lies in the unusual situations in which the measurements were made and their application to the study of the evolution of snow and ice.

So meager are the results as compared with the enthusiasm requisite to obtain them that the following valedictory of the Zurich Glacier Commission may well be quoted as ours: "Our Glacier Commission is growing in years; marked not by the number of our annual reports, nor by the pains it has cost nor the sweat, and the weight of the pack, but by the satisfaction with which our insight into the mutual working of glacier growth and melting is deepening year by year."

The observations at high altitudes were made in connection with the study of the effect of mountains and forests upon the conservation of snow and are confined to the slopes of Mount Rose and the Lake Tahoe Basin in the Central Sierra Nevada during the years of 1910-17, under the patronage of the Nevada Agricultural Experiment Station.

The observations at high latitudes were made as a by-product of the study of the glacial anti-cyclone in Greenland by the Michigan-Greenland Expedition in 1926-29 through the generosity of its Director, Professor William H. Hobbs, and Helge Bangsted, Leader of the Winter Expedition to the Inland Ice. Assisting the writer were S. P. Fergusson in 1926, Clarence R. Kallquist in 1927-28, and William S. Carlson and Leonard R. Schneider in 1928-29. The continuation of the record through the summer and winter of 1928-29 was due to the enthusiasm of Carlson who had gladly become the writer's understudy in the work.

Equipment

The equipment consisted in the main of cylindrical pans painted white and buried to their rim in the snow. These were 15 inches in diameter, thus bearing an area-relationship to the snow-sampler of 100:1 and making possible the use of the snow-sampler spring-balance to weigh the pans in terms of inches of water. The early pans were 10 1/2 inches in diameter, and in Greenland the exigencies of the situation made necessary the supplemental use of kerosene cans with one side removed.

Hoods were early used to prevent falling snow from entering the pan and so assure a record from at least a portion of the pans during periods of storm. Thus inadvertently by the use of companion-pans--one hooded, the other open--measurements of condensation became possible at times when the net evaporation was in excess.

False bottoms also were designed to hold the snow above the bottom of the pan and thus prevent the snow from becoming saturated with water when melting occurred. However, these bottoms seemed rather to accelerate the melting and were promptly abandoned. The more recent plan used by Professor Joseph Kittredge, Jr., and possibly by others, will probably avoid this weakness. It consists of using an evaporation-pan with perforated bottom and a catch-basin beneath. However, unless the catch-basin is tightly connected with the upper pan, there is risk of water entering from the snow-field in which the pan should be buried.

To avoid excessive weight, the ice-pan was given only half the depth of the snow-pan.

A tree-pan was devised by employing a circular coarse screen of the same diameter as the standard snow-pans but with a catch-basin beneath to intercept any snow that might fall from the screen during the experiment. The whole was then hung from a trolley between the crowns of the trees, the screen simulating the open branches upon which snow was clustered.

So far as available, portable field-anemometers were placed by the side of the pan, especially on mountain slopes where the wind-movement varied with topography.

However, the temperature was obtained from a central station. The relative humidity at Tahoe was obtained from a meteorograph on Observatory Point somewhat remote from the field of evaporation. Records on Mount Rose were obtained from the Observatory meteorograph but at best are fragmentary. Fortunately, however, wind- and temperature-records were also made near some of the evaporation-pans. The original plan was to determine the relative evaporation with typical slopes and forestation. Consequently, complete weather-details were not considered as a prime requisite in the series of measurements and could have been gathered only with great difficulty and expense.

The chief source of error may lie in the spring-balance which was the only portable scale available, springless balances being too cumbersome. However, the error of the individual measurements will ordinarily be small because each measurement is confined to a small section of the dial, and in case of the mean of the monthly series, the error should practically vanish.

Factors

The influence of the various weather-factors can best be determined by laboratory methods and the evaporation for definite climatic regions computed from their weighted effect. But Nature is titanic and the age of adequate laboratories is only now at hand. Furthermore, Nature is the best proving-ground of the theories of her phenomena.

But complicating the ordinary factors of humidity, wind-movement, and temperature was the instability of the material being studied: Dry snow, wet snow, shrinking snow, snow in trees and on the ground, slush, water, ice (both wet and dry). To this was added the increasing wall-area of the heat-radiating pan; and also the exposure of the pan to precipitation, which could not always be measured with certainty. Finally, gales might erode the snow from the snow-pans or in rare instances melt the ice in the ice-pans and evaporate the resulting water rapidly. From this shifting material came reluctantly but obviously means of determining the relative rates of evaporation and condensation, of evaporation and fall of snow from trees, of the acceleration of evaporation of both snow and ice with melting, and the relative rate of evaporation and melting of both snow and ice at high altitudes and its bearing on the growth of pits. However, the problem of keeping the instability within the limits set in the slow evolution of snow and ice is still difficult, for the use of relatively small pans accelerates melting and tends to reduce to slush what if outside the pan and in a continuous field would still at worst be only moist snow and ice.

Special problems

Special problems were inevitable but remunerative. Several will be mentioned with brief tables and comments.

(1) Effect of shrinking of snow in pan--Snow in a metal pan even if the latter is white will quickly retract from the sides and tends to settle. Therefore, a test of "Evaporation in pans filled to various depths" was made as shown in Table 1.

In the aggregate of experiments, the pan half-filled seemed to lose less than the full pan whereas the pan quarter-filled lost more. Possibly in the case of the pan

Table 1--Rate of evaporation in pans filled to various depths, Tahoe City, March 1917

Date	Character day	Precipitation	Mean temperature	Wind		Relative humid.	Length period	Pine forest (semi-open) evaporation		
				Direction	Velocity			Full pan	Half pan	Quarter pan
1917		inch	°F		mi/hr	o/o	hrs	inch	inch	inch
Mar. 1	Pt cl'dy	...	16.0	E	6.11	71.0	23.1	.012	.010	.010
2	Clear	...	19.5	E	4.25	56.5	23.9	.020	.014	.020
3	Clear	...	38.0	E	....	57.5	26.2	.018	.033	.080
4	Overcast	...	33.5	W	2.54	79.5	21.8	.106	.011	.013
5	Cl'dy to clear	...	22.0	W	3.25	69.5	30.2	.058	.048	.042
6	Pt cl'dy	...	25.5	NW	2.07	52.0	18.2	....	.016	.010
7	Pt cl'dy	...	31.5	NW	2.62	71.0	25.2	.034	.032	.082
Totals			186.0		20.84	457.0		.248	.164	.257
Averages			26.6		3.47	65.3				
Divergence from full pan								....	-.084	+.009
Mar. 14	Cl'dy to clear	.03	12.5	S	13.32	....	24	.002	.032	.010
15	Cl'dy	...	14.5	W	2.89	....	25	.032	.026	.030
16	Clear	...	22.0	W	0.89	59.5	24.1	.014	.022	.022
17	Pt cl'dy	...	30.0	SW	....	75.0	23.2	.027	.025	.020
Totals			79.0		17.10	134.5		.075	.105	.082
Averages			19.8		5.70	67.2				
Divergence from full pan								....	+.030	+.007
Mar. 25	Clear	...	32.5	NW	2.42	78.0	23	.017	.014	.116
26	Pt cl'dy	...	35.0	NW	2.67	71.0	23.9	.030	.011	.032
27	Pt cl'dy	...	32.5	NW	2.45	....	23.6	.025	.028	.075
28	Clear	...	42.5	W	2.65	84.5	....	....	....	....
Totals			142.5		10.19	233.5		.072	.053	.223
Averages			35.6		2.55	77.8				
Divergence from full pan								....	-.019	+.151
Mar. 30	Cl'dy	...	20.0	SW	2.77	67.0	24.9	.027	.026	.032
31	Cl'dy	...	26.5	SW	....	61.5	22.5	.046	.022	.022
Totals			46.5		2.77	128.5		.073	.048	.054
Averages			23.25		2.77	64.2				
Divergence from full pan								....	-.025	-.019
Apr. 2	Cl'dy	...	27.5	SW	3.96	85	23.5	.018	.003	.172
4	Clear	...	35.0	E	3.51	76	24	.120	.035	.258
5	Clear	...	38.5	W	3.88	77	25.2	.038	.020	.787
6	Clear	...	37.0	W	1.92	65	22.2	.020	.008	.002
9	Cl'dy	...	28.5	SW	3.00	82	24.9	.021	.030	.515
10	Pt cl'dy	.02	39.5	N to W	4.92	91	24	.000	.005	.108
Totals			206.0		21.19	476		.217	.101	1.842
Averages			34.3		3.53	79.3				
Divergence from full pan								....	-.116	+1.625
Grand totals								.685	.471	2.458
Grand averages			27.9		3.60	70.8				

Table 2--Comparison of hooded and exposed pans or evaporation and recondensation, Tahoe City, March 1917

Period	Character day	Relative humid.	Mean temperature	Day				Night			
				Wind-veloc.	Hooded pan	Exposed pan	Excess hooded	Wind-veloc.	Hooded pan	Exposed pan	Excess hooded
1917		o/o	°F	mi/hr	inch	inch	inch	mi/hr	inch	inch	inch
Mar. 1-7	Pt cl'dy	64.5	26.6	4.10	0.147	0.165	-0.018	0.09	0.144	0.066	+0.078
8	Cl'dy	95.0	30.0	1.62	0.055	0.057	-0.002	....	.....	.....	......
15	Cl'dy	63.5	14.5	....	.....	.....	......	0.03	0.018	0.000	+0.018
18	Pt cl'dy	83.0	29.0	....	.....	.....	......	0.09	0.015	0.008	+0.007
22-27	Clear	68.6	30.3	0.43	0.102	0.084	+0.018	0.07	0.096	0.063	+0.033
28	Clear	84.5	42.5	0.56	0.007	0.015	-0.008	....	.....	.....	......
Totals, 17 days		459.1	172.9	6.71	0.311	0.321	-0.010	0.28	0.273	0.137	+0.136
Averages		76.5	28.8	1.68				0.07			

Note: Hooded pan and exposed pan represent gross and net evaporation, respectively; divergence shows roughly the condensation.

Table 3--Average of evaporation, Tahoe City, January and February 1917

Conditions	Period	Wind-velocity	Station 1		Station 2		Excess evap'n hooded over exposed pans	
			Pan 1 hooded	Pan 2 open	Pan 1 hooded	Pan 2 open	Sta. 1	Sta. 2
	days	mi/hr	inch	inch	inch	inch	inch	inch
Calm	6	...	0.0125	0.0095	0.041	0.025	+0.0030	+0.016
Wind	..	1.0	0.022	0.0205	0.046	0.050	+0.0015	-0.004
Under 1½ mi	18	1.5-	0.0185	0.011	0.043	0.039	+0.0075	+0.004
Cl'dy; over 1½ mi	10	1.5+	0.033	0.0165	0.043	0.038	+0.0165	+0.005
Clear	..	1.0	0.021	0.011	0.033	0.028	+0.010	+0.005
Cl'dy	..	1.33	0.015	0.003	0.050	0.026	+0.012	+0.024

half-filled, the protection from wind outweighed the effect of radiation of heat from the sides of the pan while in the case of the pan quarter-filled the reverse was true. It would be well to make this test under conditions of continuing shade as well as in the more normal semi-open forest.

(2) Divergence in evaporation in hooded and open pans--The general appearance of the hooded pan is shown on page 535 of the October 1933 issue of the Geographical Review. Its purpose was to prevent unexpected snowfall from ruining the experiment. Its result was to make possible the measurement of evaporation occurring during precipitation--a thing impossible unless very accurate measurement of the precipitation in an adjoining pan can be made.

The startling result was the discovery that the evaporation from hooded pans was usually greater than from exposed pans. The apparent explanation was not that heat beneath the hood increased the rate of evaporation but rather prevented condensation, which was unobstructed on the exposed pan. Or, stated in other terms, the pan beneath the hood was protected from losing its latent heat so rapidly by radiation.

It opened up the fact of relative evaporation and condensation, both active, each at times gaining the ascendency. Thus the loss or gain of the exposed pan might be called net evaporation or net condensation, respectively. In actual effect, as shown in Table 2, the difference between the two types of pans is slight during the day but greater by night. In a further test of differing conditions of wind and cloudiness during the two months of January and February, the hooded pans showed an excess. However, no test was made between day and night.

In measuring total seasonal evaporation, the hooded pan will be found fairly accurate and practically continuous in operation. The following summary of evaporation for the entire season of December 1915 to May 1916 at Marlette Lake (8000 feet) on the eastern rim of Lake Tahoe will illustrate: Total evaporation during the six months at Station 1 was 8.288 and 6.506 inches and at Station 2 was 9.959 and 9.370 inches, for hooded pan and for exposed pan, respectively, giving average monthly evaporation of 1.381, 1.084, 1.659, and 1.561 inches, or average values from the two stations of 1.520 inches for hooded pan and 1.323 inches for exposed pan.

(3) Excess of condensation and evaporation--Only in quantity does condensation differ from precipitation. The technique seems the same, and only occasionally does condensation exceed evaporation in the two regions covered. In the storm-track where moisture is superabundant, the condensation may be in excess. On mountain tops also where clouds linger, condensation may be excessive for a season, as shown by frost-feathers on the summit of Mount Rose (10,800 feet). The condensation prevailed for a thousand feet down the mountain where it feathered out. But this was a rare occurrence, though slight condensation, known as pogonip, is normally prevalent during storm-periods and their clearing.

However, only rarely has the total condensation for a month even in winter exceeded the total evaporation, as shown by the measurements for Greenland (Tables 12 and 13), where detailed records of the two have been made throughout the year.

(4) Evaporation of snow in tree crowns--The evaporation or wastage of snow in tree crowns was one of the first refinements in the study of the relation of forests to the conservation of snow. The tree-pan as developed made it possible not only to study the evaporation but also the falling of the snow from the crowns through Sun or wind. It was realized that in trees of ordinary density much of the snow ultimately reaches the ground. This is quite the opposite of rainfall which is promptly absorbed or evaporated.

The relative evaporation of snow from tree crowns and from the snow on the ground is shown in Tables 4 and 5. In general, the evaporation in the tree crowns is twice as great as on the ground but on occasion may be six or even more times as great.

The amount of drip or fall of the snow will naturally depend upon the wind or Sun, but is known from actual observation to be large. This has actually been measured by snow-surveys in a treeless meadow, in a forest of pine and fir, and in a denser fir forest, all adjoining. The measurement March 11, 1910, before melting had begun was: Treeless meadow 11.7 inches; forest of pine and fir 12.1 inches; and fir forest 11.0 inches. However, the two measurements of drip given in Tables 4 and 5 indicate that the snow was still firmly clinging to the trees. Naturally evaporation-measurements in tree crowns must be made only in relative calm or light breezes. A heavier wind would blow snow from the branches upon the pan or even erode its contents. At such a time, however, the forest crowns are quickly unloaded of their snow-burden.

(5) The effect of topography and forestation--The study of evaporation with altitude or even latitude is further complicated by topography and forestation.

The effect of topography is vividly emphasized by the wind-relationship on the summit of Mount Rose and on either side, as measured April 20, 1914. There the wind-velocities in miles per hour during the night and during the day were, respectively: Summit, 68.3 and 70.5; south side, 51.1 and 55.8; north side, 12.7 and 13.0. For this and other evidence, reference may be made to Table 9.

The effect of forestation is likewise shown by reference to Table 9, and particularly to Table 6. The variation is extreme. As between a dense fir-forest and open meadow, the evaporation in the latter is three times that in the former. For example, in the month of March, as averaged for the years of 1911-17, the following mean monthly evaporations were measured: Fir forest, 0.469 inch; pine forest, 0.788 inch; pine and fir forest, 0.666 inch; meadow, 1.303 inches.

(6) Relative rate of evaporation and melting at high altitudes--Only slight evi-

Table 4--Comparison of evaporation in tree crowns and on ground, 1915

Date	Character day	Mean temperature	Wind		Precipitation (water)	Period	Evaporation		
							Tree-pan		Ground-pan*
			Direction	Velocity			West	East	
1915		°F		mi/hr	inch	hrs	inch	inch	inch
Jan. 21	Clear	28	NE,E	0.63	....	23	0.027[a]	0.055[b]	0.015
Mar. 4	Clear	28.5	W	1.56	....	22.2	0.206[c]	0.088[d]	0.056
							North	West	
25	Pt cl'dy	40.5	W	0.9	....	23.3	0.101	.....	0.023
26	Pt cl'dy	35.5	W	0.9	0.03	18.3	0.018	.....	0.022
27	Cloudy	36.5	S	...	1.075	....	.....	.....	.....
28	Cloudy	32.5	SW	...	0.20	....	.....	.....	.....
29	Pt cl'dy	27.5	SW	...	0.01	....	.....	.....	.....
30	Pt cl'dy	36.5	SW	...	....	94	0.172[e]	0.182	0.142
31	Pt cl'dy	40.0	W	...	0.45	....	.....	.....	.....
Average	....	34.7	...	...	0.353	....	0.124	0.135	0.061
Apr. 1	....	....	...	...	....	49	0.163[f]	0.205	0.093

*Ground-pan under hood. [a] Drip from tree, 0.012 inch. [b] Drip from tree, 0.017 inch. [c] Drip from tree, 0.88 inch. [d] Drip from tree, 0.03 inch. [e] Average, 0.043 inch per 24 hours. [f] Average, 0.082 inch per 24 hours.

Table 5--Comparison of evaporation of tree crowns and on ground, 1917

Date	Character day	Mean temperature	Wind		Precipitation	Rel. humidity	Tree-pan		Ground-pan	
			Direction	Velocity			Period	Evaporation	Period	Evaporation
1917		°F		mi/hr	inch	o/o	hrs	inch	hrs	inch
Feb. 8	Clear	31.0	W	2.42	....	87.5	24.3	0.003	26.2	0.001
9	Clear	30.5	W	2.04	....	67.0	24.3	0.077	24.3	0.000
10	Clear	31.0	W	1.21	....	69.0	27	0.140	26	0.025
27	Cloudy	20.0	W	2.96	....	78.0	23.5	0.067	21.5	0.008
Average	....	28.1	..	2.16	....	75.4	....	0.072	....	0.008
Mar. 1	Pt cl'dy	16.0	E	0.15	....	71.0	23.5	0.050	23.8	0.012
2	Clear	19.5	E	0.10	....	56.5	23.2	0.080	23.2	0.013
3	Clear	38.0	E	0.07	....	57.5	26.2	0.032	26	0.011
4	Overcast	33.5	W	0.31	....	79.5	21.9	0.060	21.9	0.012
5	Cloudy[a]	22.0	W	0.40	....	69.5	23.9	0.058	30.2	0.054
6	Pt cl'dy	25.5	NW	0.02	....	52.0	24.5	0.066	18.2	0.017
7	Pt cl'dy	31.5	NW	0.31	....	71.0	25.2	0.069	11.3	0.016
15	Cloudy	14.5	W	0.06	....	....	18.5	0.018	24.8	0.045[b]
16	Clear	22.0	W	0.03	....	59.5	24.7	0.060	24.3	0.035[b]
17	Pt cl'dy	30.0	SW	0.21	....	75.0	22.6	0.065	22.7	0.060[b]
18	Pt cl'dy	29.0	SW	0.33	....	73.0	23.2	0.020	23.3	0.055[b]
23	Clear	29.0	NW	0.09	....	59.0	23.6	0.037	24.6	0.035
Average	....	25.9	..	0.173	....	65.8	....	0.050	....	0.021

[a] Cloudy to clear. [b] Values so marked are hooded pan and give an average value of 0.049.

dence on this point has been obtained on Mount Rose. However, much could readily be obtained. The bit of evidence found in available data favors Mr. Matthes' contention. For example, on the summit of Mount Rose, March 4-5, 1914, the following measurements of evaporation of snow were obtained: North slope, wind 13.30 miles hourly, daily evaporation 0.110 inch, monthly rate 3.303 inches; south slope, wind 7.82 miles hourly, daily evaporation 0.186 inch, monthly rate 5.567 inches (note melting film). Since the wind on the south side of summit is usually from two to four times as strong as on the

Table 6--Effect of forestation and evaporation, Lake Tahoe, 1910-17
(Figures below entries of data indicate number of years and average days per month)

Month and year	Pine forest				Fir forest			Pine and fir			Meadow			
	Open near river	Large opening	Medium open.	Medium forest	Typical	Small fir-glade	Small opening	Typ. course 2	Small opening	North of hedge	Open	Upper[a)]	Thick fir	South slope deforested
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
Nov. 1916	0.670 1- 7.1	.....	.....	.....	.....	0.180 1- 5.9	.....	.....	.....	.....	.....	.....	.....	.....
Dec. '15-'16	0.403 2-13.6	0.155 1- 2	.....	.....	.....	0.207 3- 9.5	.....	0.013 1-10.1	.....	.....	0.992 3- 5.4	0.481 2- 6.3	.....	2.510 1- 0.9
Jan. '12-'17	0.721 4-13.8	0.233 2- 4	.....	0.289 3-12.5	.....	0.196 3-12.2	.....	.....	.....	.....	1.634 4-12.5	0.651 1-29.1	.....	.....
Feb. '11-'17	0.782 4-13.8	0.549 3-22.6	0.493 1-24.5	0.914 3-13.9	0.224 1-14.2	0.275 3-17.8	.....	0.209 1-10	.....	.....	1.051 3-22.7	0.712 2- 9.1	.....	.....
Mar. '11-'17	1.004 4-24.7	0.940 3-20.9	0.589 1- 9.5	0.620 3-25.9	0.372 1-22.4	0.566 4-27.3	.....	0.666 1-26.5	.....	.....	1.490 4-22.5	1.255 2-23.9	0.372 1-30.9	1.116 1-28.9
Apr. '10-'17	0.964 4-21.8	0.610 3-16.9	0.450 1- 6.2	0.580 3-25.5	0.555 2-25.4	0.386 5-22.5	.....	0.720 1-28.7	.....	0.570 1-21.7	1.308 5-16.7	0.960 2-28.1	0.390 1-26.9	0.630 1- 5.9
May '13-'17	0.775 1-12.5	0.310 1- 8.2	.....	0.684 2-14.5	0.403 1-22.8	0.356 2-17.8	.....	.....	.....	0.604 2-13.8	1.116 2- 5.7	.....	.....	0.620 1-19.3
June '10-'17	.....	1.080 1-	0.810 1-	.....	.....	0.630 1-	0.510 1- 6.6	.....	1.140 1- 8.0	1.140 1-10.0	.....	.....	.....	.....
Average, Mar. '11-'17		0.788				0.469			0.666			1.058		

a)Upper meadow with cedar, pine, and fir.

north, the probability is that the anemometer had made an additional complete revolution of 990 km or 12.79 miles per hour. The corrected wind-movement would thus be 20.61 miles per hour--a satisfactory relationship to the record on the north.

Here, then, we find a not unusual wind-movement of 20 miles an hour and an evaporation-rating practically one-fifth inch water-content daily with only a film of melting visible. In terms of ice-depth alone, the apparent evaporation would be slightly greater.

Table 7--Comparative monthly mean rates of evaporation of snow and ice, January to May 1917

Year and month	Temperature	Rel. humidity	Near river mouth				Open meadow			
			Wind-veloc.	Snow-pan	Wind-veloc.	Ice-pan	Wind-veloc.	Snow-pan	Wind-veloc.	Ice-pan
1917	°F	o/o	mi/hr	inch	mi/hr	inch	mi/hr	inch	mi/hr	inch
Jan.	21.5	75.2	1.39	0.468	4.72	1.392	....	1.398	1.48	0.708
Feb.	29.2	76.3	0.82	0.294	....	1.26	....	1.44	0.76	0.570
Mar.	26.9	71.4	0.254	0.984	....	1.665	1.23	1.11	....	0.81
Apr.	36.1	75.0	0.219	0.468	....	1.134	2.04	0.807	....	1.767
May	41.3	....	3.25	0.561	....	.....	....	.....	....	.....
Average	31.0	74.5	1.187	0.555	4.72	1.363	1.635	1.189	1.12	0.964

Similar data from high latitudes depend upon the union of low temperature and high wind-velocity. Unfortunately, in Central Greenland, both on the coast and the edge of the Ice Cap, the winds of high velocity are usually foehn or stroph winds descending from inland Greenland and have a temperature ordinarily above freezing. However, the rippled ice is abundant evidence of the evaporating effects of the wind and no corresponding runoff was observed.

It is possible that the ice-ripples of the north are the counterpart of the "pits" of the south. The more rapid action in the north may tend to reduce the surface more uniformly.

(7) Instability of snow and ice and consequent variation in expected rate of evaporation--An attempt has been made to determine the relative rate of evaporation of new and old snow, but thus far the evidence is inconclusive. More delicate and exact weighing apparatus may be required.

However, the presence of water even in a film seems to raise the rate both of snow and of ice. Thus probably the ripple marks on the ice in the north. In Greenland, the evaporation rate for ice was ordinarily one-half of that for snow. But as shown in Table 7, the rate of evaporation of ice varies from one-half to double that of snow. The cause was not at first apparent, but copious notes taken at the time reveal either the presence of water in the ice-pans or physical changes in the ice possible only by melting during the observer's absence. Many of the crystallizations were so exquisite as to cause the observer to portray them in his record.

Brief but convincing evidence is the following record from Contact Pass (9000 feet) on Mount Rose: Ice on April 14, 1914--Temperature was 25°.5 F (minimum), wind was 6.69 miles hourly, and daily evaporation was 0.021 inch or a monthly rate of 0.624 inch; slush on April 16-17, 1914--temperature was moist to 13°.3 F, wind was 1.80 miles hourly, and daily evaporation was 0.120 inch or a monthly rate of 3.588 inches. The rate of evaporation for slush was even under colder and calmer conditions over five times that for ice. Yet the temperature of both ice and slush was probably not above 32° F.

The main problem

Unfortunately, in the study of the change in rate of evaporation with increase either in altitude or in latitude only occasional and fragmentary measurements are available. In the case of altitude continuous measurements only at the lower levels are available. Furthermore, the high-level measurements were begun earlier in connection with conservation studies on Mount Rose.

Continuous and simultaneous measurements are naturally best. Next are climatic records either long or covering the same period of years. Finally records of evaporation with only a single factor divergent--such as wind--are acceptable.

For fundamental comparisons, three similarly environed stations should be simultaneously maintained and preferably through at least a year. Yet even so, the climate

Table 8--Comparative monthly mean measurements of climate and evaporation of snow at Lake Tahoe (6225 feet) and Marlette (8000 feet)

Year and month	Lake Tahoe				Marlette			
	Temperature	Wind-velocity	Rel. humidity	Evaporation[b]	Temperature	Wind-velocity	Rel. humidity	Evaporation[b]
	°F	mi/hr	o/o	inch	°F	mi/hr	o/o	inch
Dec.[a] 1915	29.3	2.59	72.8	1.035	31.8	2.12	64.2	0.529
Jan.[a] 1916	22.0	1.52	80.0	1.29	29.6	1.05	85.8	0.795
Feb. 1916	35.1	....	76.7	1.455	35.6	1.58	84.2	1.35
Mar. 1916	35.8	1.89	80.3	1.45	34.1	1.97	80.2	2.43
Apr. 1916	40.1	2.65	78.7	1.745	37.3	3.52	79.4	1.575
Average	32.46	2.16	77.7	1.395	33.68	2.048	78.76	1.336

[a] Month incomplete. [b] Average from two evaporation-pans in open forest.

of individual months will not be comparable because of the vertical march of the seasons. Only the aggregate for the year seems satisfactory. In the paucity of data, all available methods will be employed and a comparative chart of the climate will be attempted.

I--EVAPORATION AT HIGH ALTITUDES

The region of high altitudes for which data have been obtained comprises the northwest shore of Lake Tahoe at Tahoe City (6225 feet), Marlette Lake on its eastern rim (8000 feet), and Mount Rose overlooking the lake from the northeast (crest-elevation of 9000 to 10,800 feet).

The controlling factors are low temperature and high wind versus high temperature and low wind, the former being characteristic of high altitudes and the latter of the low.

Climate of Tahoe and Mount Rose

The climate of Mount Rose and Lake Tahoe, the representatives of each, so far as can be presented by fragmentary chart is as follows: Lake Tahoe (6225 feet)--Temperature 41°.5 F, wind 2.03-4.60 miles per hour in river mouth at outlet, relative humidity 78.65 per cent (November to April); Mount Rose (10,800 feet)--temperature 29°.5 F, wind 20.05 miles per hour (July and October), relative humidity 80.60 per cent (April and October).

Because of the forestation on the shores of Lake Tahoe where the evaporation-measurements have been made, the wind even in the river mouth at its outlet is somewhat high. Likewise the relative humidity, for it represents only the season of heavy precipitation. On the other hand, both wind and relative humidity on Mount Rose must be too low because confined to the milder months of spring, summer, and autumn. However, the climatic conditions on the topmost summit of Mount Rose are more severe than in the area immediately below where most of the measurements of evaporation were made. Therefore, the fragmentary chart of climate doubtless will be more representative of the comparative climate prevailing at Lake Tahoe and Mount Rose.

It will be noticed that the difference in relative humidity is not large. However, the difference in mean temperature is somewhat greater, sufficient in the case of water-evaporation to lower the rate on Mount Rose considerably, especially since the water will come directly from the snowfields and rapidly descend. However, the wind-movement is startlingly larger on Mount Rose than at Tahoe--at least, it is ten miles per hour greater.

On the basis of investigations by Burton E. Livingston at the Carnegie Desert Botanical Laboratory (Carnegie Institution Pub. 50, 1906) "a velocity of 4.6 meters per second (approximately 10 miles per hour) increased evaporation 250 per cent and a

Table 9--Measurements of evaporation at stations on Mt. Rose, water-years 1909-10 and 1913-14

Station	Elevation	Date	Temperature	Wind-velocity	Evaporation		Remarks
					Daily	Monthly	
	feet		°F	mi/hr	inch	inch	
		Water-year 1909-10					
Kennedy Pass	9300	May 2- 4, 1910	31.9	12.65	0.180	5.412	
Summit	10800	June 8- 9, 1910	33.8	10.04	0.185	5.541	
Kennedy Pass	9300	June 13, 1910	....	3.73	0.060	1.800	Average=2.480 inches
			....	2.35	0.032	0.972	
Contact Pass	9000		....	3.66	0.054	1.605	
		Effect of forestations					
Dome	10000	June 10-11, 1910	48.0	2.69	0.063	1.881	
			....	3.74	0.070	2.100	Average=2.112 inches
Open hillside	9500	June 12, 1910	....	6.24	0.103	3.090	
Ideal forest glade		June 12, 1910	....	2.04	0.046	1.377	
		Water-year 1913-14					
Contact Pass	9000	Dec. 28-29, 1913	20.0	7.0	0.027	0.800	Snow-pans, average = 1.200 inches
			20.0	7.0	0.053	1.599	
		Dec. 30, 1913 to Jan. 4, 1914	26.7	50 to light	0.040	1.185	Ice-pans, blizzard to fair
		Jan. 4 to Mar. 2, 1914, 30 days	....	....	0.0051	0.153	Ice-pan in hut
Summit	10800	Mar. 3- 5, 1914	....	13.30	0.110	3.303	North slope
			....	7.82	0.186	5.567	South slope
Talus Slope	10800	Mar. 5, 1914	....	....	0.079	2.382	Snow-pans, average March = 2.950 inches
Kennedy Pass	9300	Mar. 4- 5, 1914	....	....	0.118	3.540	
Contact Pass	9000	Mar. 5, 1914	32.3	4.65	0.030	0.906	
			....	....	0.067	2.001	
			....	....	0.094	2.825	Ice-pan (floating ice over 2/3 of pan)
Summit	10800	Apr. 13-21, 1914	....	10.18	0.081	2.430	Includes prec. 0.038 inch
					0.092	2.748	Gross
		Apr. 24-25, 1914	....	....	0.022	0.660	Includes frost
					0.036	1.080	Excludes frost
		Apr. 18-25, 1914	....	9.43	0.089	2.679	North side
			....	27.35	0.302	9.054	South side
							Average all Summit April = 3.109 inches
Talus Slope	10800	Apr. 15-19, 1914	24.3	....	0.094	2.805	
Kennedy Pass	9300		....	....	0.082	2.451	
Contact Pass	9000	Apr. 14-17, 1914	....	3.71	0.059	1.776	
					0.047	1.291	
		Apr. 14, 1914	25.5	6.69	0.021	0.624	Ice
		Apr. 16-17, 1914	13.3	1.80	0.120	3.588	Slush
		May 29 to June 5, 1914	38.5	4.04	0.061	1.820	Snow, average 4 pans
					0.075	2.241	Slush, average 2 pans

Note-- Wind-relations to slopes at Summit (10800 feet), April 20, 1914: Night-free air 68.3, north side 12.7, south side 51.1; day-free air 70.5, north side 13.0, south side 55.8 (in miles per hour).

velocity of 8.0 meters per second (approximately 18 miles per hour) increased it 450 per cent." If temperature and humidity were alike at the two elevations, Mount Rose should show an evaporation 2.5 times greater than at Tahoe.

This corresponds fairly well with an actual test at Contact Pass (9000 feet) on Mount Rose (see Table 9) December 30, 1913 to March 5, 1914. A pan of ice was exposed for six days in a wind varying from 50 miles (or furious) to 20 miles for three days, strong for two days, and light for one day, or probably approximately 25 miles per hour for the period. It was a period of blizzard. Hence the humidity was high. Then the pan was hung in a sand-bag hut tightly closed for 30 days while the party was absent.

The air-current here, save for a stovepipe current deadened by a damper and closed draft, was negligible. The result was as follows: December 30, 1914 to January 4, 1915--temperature 26°.7 F, wind 50 miles hourly to light, daily evaporation 0.040 inch or monthly rate 1.200 inches; January 4 to March 2, 1915--minimum temperature 23°.1 F, wind calm in hut, daily evaporation 0.0051 inch or monthly rate 0.153 inch. Divergence with wind of approximately 25-mile difference = 784 per cent.

(1) *Comparison of evaporation-rates of snow at Lake Tahoe (6225 feet) and Marlette Lake (8000 feet)*--Because of its higher location and potential exposure to greater wind, it had always been assumed by the writer that the evaporation-rate of snow at Marlette Lake was higher. However, on the basis of similar environments, that is, of open timber, which prevails at Marlette Lake, the average seasonal rates are almost identical, as shown in Table 8, namely, 1.395 inches monthly (December 1915 to April 1916) for Tahoe and 1.336 inches for Marlette. The rates also for mean temperature, wind, and relative humidity are practically identical.

However, in the case of water-evaporation during the period June to September 1917, with similar mean monthly temperature and wind, the evaporation at Marlette was 50 per cent higher. The exact measurements are: For Tahoe--mean temperature 57°.9 F, wind 2.8 miles hourly, total evaporation 21.83 inches or 5.458 inches monthly; for Marlette--mean temperature 56°.5 F, wind 2.5 miles hourly, total evaporation 33.342 inches or 8.336 inches monthly.

The reason seems to lie in the fact that the pan at Tahoe was a lake-pan, kept cooled by water flowing from the deep lake, while the pan at Marlette, as later learned, was a land-pan exposed bottom and sides to the air and in Sun practically the entire day. Unfortunately, no temperature-measurements of the water in the Marlette pan were recorded.

However, this problem does not prevail in the present study, which concerns snow and ice, both consistently near the point of freezing. But even water naturally situated would not be so divergent as in this comparison.

(2) *Comparison of evaporation-rates of snow at Lake Tahoe (6225 feet) and Mount Rose (10,800 feet)*--As shown above in discussing the climate for Lake Tahoe and Mount Rose, the wind-variation between these two elevations is large.

Unfortunately, the data on Mount Rose are fragmentary (see Table 9) and the wind as measured is relatively low, for evaporation-measurements at the higher rates of wind are practically impossible. Yet the average of the monthly rates of the various series taken of snow-evaporation during 1910-11 and 1913-14 is 2.759 inches as compared with the mean monthly seasonal rates of 0.759 inch in open forest and 1.265 inches in open meadow at Lake Tahoe--environments most nearly like that on Mount Rose. The evaporation on Mount Rose is, therefore, fully from two to four times as great as at Lake Tahoe on the most favorable basis possible. In fact the evaporation-measurements were made with a single exception on the leeward side of the mountain.

II--EVAPORATION AT HIGH LATITUDES

The field of study was Central Greenland at the Arctic Circle and reached from the seacoast to a few miles upon the Inland Ice. The altitude ranged from sea-level to 1500 feet. The longest records were obtained in inner Greenland on Mount Evans at the elevation of 1200 feet.

Topographically, the area is divided into coastal, and gradually rising inland, culminating in the Inland Ice which reaches an elevation of 2500 meters on the route traversed by De Quervain. A coast-range (600 to 1300 m in height) separates the coast from the inland, leaving the latter somewhat drier according to a snow-survey conducted from the Inland Ice to the sea. The relative precipitation on the crest of the Inland Ice in this sector has never been determined.

The main posts of observation of the climate have been Holstensborg on the coast, and Mount Evans (1200 feet) 70 miles inland at the head of Kangerdlugsuak Fiord. A short-time station was maintained in the summer of 1926 near the head of Ikertok Fiord at Camp Michigan, whence a trip of three weeks was made to the Inland Ice to a point

Table 10A--Comparative climate of Holstensborg, Camp Michigan, and Inland Greenland, July 27 to August 17, 1926

Station	Temperature		Relative humidity	Wind-velocity	Precipi-tation
	Mean	Range			
	°F	°F	o/o	mi/hr	inch
Holstensborg	49.4	9.6	....	...	....
Camp Michigan	48.6	17.8	70.6	...	....
Inland Greenland	49.2	18.7	63.7	3.9	0.04

Table 10B--Comparison of temperature and humidity at Holstensborg, Camp Michigan, and Inner Greenland, July 27 to August 17, 1926

Date	Temperature						Relative humidity	
	Holstensborg		Camp Michigan		Inner Greenland		Camp Michigan	Inner Greenland
	Mean	Range	Mean	Range	Mean	Range		
1926	°F	°F	°F	°F	°F	°F	o/o	o/o
July 27	45.7	6.3	49.5	9.5	52.8	11.3	77.7	53.3
28	50.0	4.5	46.8	11.0	52.2	21.0	86.0	61.8
29	51.1	2.0	46.1	19.0	51.6	14.5	85.9	62.4
30	49.5	3.4	47.6	28.0	49.1	21.7	80.0	63.6
31	51.1	2.2	45.2	17.0	47.1	22.0	86.9	62.3
Aug. 1	53.8	2.7	49.7	19.0	48.2	19.0	84.5	64.9
2	53.6	2.2	50.9	31.0	48.7	27.4	62.4	59.6
3	53.1	1.6	50.4	14.0	47.5	29.6	61.3	56.8
4	52.2	1.4	49.8	32.0	46.7	21.0	65.3	59.0
5	55.6	3.4	53.4	33.0	48.7	16.2	57.0	53.9
6	54.5	3.1	54.6	16.0	52.5	7.8	69.1	44.7
7	54.3	5.6	47.8	8.5	48.1	7.5	80.7	57.1
8	53.1	2.5	47.8	6.0	47.3	7.5	72.1	74.3
9	50.7	1.4	51.2	14.0	51.4	17.5	57.9	66.1
10	45.9	4.5	48.3	10.0	47.6	12.7	71.8	67.5
11	44.1	5.0	46.0	21.0	49.0	25.9	65.3	69.0
12	43.7	9.2	46.0	14.5	52.5	28.0	68.4	65.5
13	47.5	7.2	43.9	14.5	47.0	12.2	70.5	77.2
14	43.9	7.0	43.9	15.0	46.2	23.0	67.6	77.5
15	44.8	10.4	47.3	17.5	46.8	17.0	65.1	78.9
16	43.9	5.9	52.4	26.0	51.7	21.0	52.4	63.6
17	44.4	5.9	50.3	14.5	50.2	27.0	64.6	62.2

named Camp Cooley. In the summer of 1927, a summer trip of one month was made from Mount Evans to the Inland Ice and in the winter of 1927-28 a trip of two months was made for the sole purpose of studying the weather.

From the observations made at the main stations and the short records obtained on the three trips to the Inland Ice have been built up climatic Tables 10A, 10B, 10C, and 10D for Central Greenland.

The mean temperature shows little divergence as shown by Table 10B. The humidity in Inland Greenland was slightly lower as was expected behind the Coast Range. The wind was low and the precipitation very light. Comparative records of wind and precipitation at the coast were not available.

This seemed to be the land of the Lotus Eaters, so kindly were the elements and evaporation-measurements made at Camp Michigan August 18 to September 2 with the attractive monthly rates of approximately 0.568-inch evaporation from the tundra and approximately 0.900-inch evaporation from open water. The evaporation-pans were set rim

Table 10C--Monthly means showing climate of Greenland at Holstensborg (H), Mt. Evans (E), Inner Greenland (G), and Inland Ice (I), August 1927 and January to March 1928

Year and month	Mean temperature				Mean daily range				Mean wind-velocity			
	H	E	G	I	H	E	G	I	H	E	G	I
	°F	°F	°F	°F	°F	°F	°F	°F	mi/hr	mi/hr	mi/hr	mi/hr
Aug.1927	46.4	44.58	46.3	37.1	8.4	16.3	19.2	5.9	5.2	8.2	3.7	4.5
Jan.1928	17.3	4.08	....	....	1.00	8.64	....	....	12.2	9.45	...	...
Feb.1928	15.2	-2.01	....	-2.8	6.68	7.93	....	12.8	10.0	6.8	...	9.2
Mar.1928	20.0	18.41	....	23.7	7.96	11.57	....	10.8	11.4	9.85	...	15.2
Average Jan.-Mar.	17.5	6.83	....	10.4	5.21	9.38	....	11.8	11.2	8.7	...	12.2

Year and month	Relative humidity				Precipitation			
	H	E	G	I	H	E	G	I
	o/o	o/o	o/o	o/o	inch	inch	inch	inch
Aug.1927	45.8	45.8	63.9	81.2	0.118	1.17	0.072	0.36
Jan.1928	54.9	81.75	....	....	0.121	0.25	.....	....
Feb.1928	52.5	82.10	....	90	.....	0.22	.....	0.461
Mar.1928	56.4	68.35	....	74.5	0.071	0.27	.....	0.114
Average or total Jan.-Mar.	54.6	77.4	....	82.3	0.192	0.74	.....	0.575

deep in the cool tundra. Consequently the result must represent natural evaporation closely. So consistent seem to be the weather-elements and the evaporation that the discussion of this experiment with detailed chart is appended (Appendix A). Comparison is also there made with the Western United States.

As shown by Table 10C, the relative conditions of climate in 1926 were duplicated in August 1927. The mean temperatures at Holstensborg, Mount Evans, and Inland Greenland showed little divergence--likewise the wind-velocity and precipitation. Only in relative humidity is there a considerable increase inland onto the Inland Ice. The range in temperature at Mount Evans and inland is higher than at the coast or on the Inland Ice. This, however, is to be expected, for the presence of the sea and the great ice retards radiation.

In the following winter (January to March 1928), the mean temperature falls inland, the wind-velocity both on the coast and the Inland Ice more than doubles its intensity, the relative humidity increases everywhere except on the ice, where it is always high, and precipitation seems to increase with distance from the sea. However, quantitatively all the elements of mean temperature, temperature-range, and precipitation are low. The humidity resembles that at Tahoe and Mount Rose. Only the wind is high, but even this is scarcely more than half of that on Mount Rose.

A three-year comparison of the climate at Holstensborg and at Mount Evans shown in Table 10D indicates a closely similar mean temperature slightly below freezing, a low daily range but larger inland on Mount Evans, a similar wind-velocity of 8 to 10 miles per hour, a relative humidity increasing from 56.13 per cent at Holstensborg to 77.4 per cent on Mount Evans, and a mean annual precipitation of less than 0.5 inch at either place, but apparently increasing eastward from the sea.

Since tradition and earlier records indicate a normal precipitation of many inches at the coast, the writer offers the following snow-survey made in March to April 1928 from the back of the Inland Ice to Holstensborg. However, it represents not so much precipitation as savings or climatic frugality. Yet the consistency of the variation in terms of the effect of barrier-ranges leads to the conclusion that even this remnant represents the relative precipitation over this sector. At least the mean wind-velocity seems as high on the coast as on Mount Evans. Furthermore, the snow-survey on Mount Evans is quantitatively half as great as the measured precipitation

Table 10D--Monthly means showing climate at Holstensborg (H) at sea-level and Mt. Evans (E) at 1,200 feet, Greenland, 1926-1929

Year and Month	Temperature		Range temp.		Wind-velocity		Rel. humidity		Precipitation	
	H	E	H	E	H	E	H	E	H	E
1926	°F	°F	°F	°F	mi/hr	mi/hr	o/o	o/o	inch	inch
July	49.4	.....	....	.....	.....	.....	....	.....	.....	.....
Sep.	41.8	.....	4.99	.....	8.9 SW	.....	54.3	.....	.....	.....
Oct.	32.1	.....	7.6	.....	7.5 SE	.....	53.6	.....	.....	.....
Nov.	22.2	.....	7.7	.....	9.5 E	.....	49.8	.....	.....	.....
Dec.	12.4	.....	6.98	.....	10.2 E	.....	51.9	.....	.....	.....
Average	31.6	.....	6.82	.....	9.02	.....	52.4	.....	.....	.....
1927										
Jan.	2.9	.....	8.6	.....	10.8 E	.....	49.4	.....	.....	.....
Feb.	3.1	.....	5.8	.....	8.2 E	.....	53.6	.....	.....	.....
Mar.	4.4	.....	5.7	.....	7.4 E	.....	45.1	.....	.....	.....
Apr.	21.0	.....	8.9	.....	7.6 E	.....	57.3	.....	.....	.....
May	35.4	.....	8.2	.....	5.4 E	.....	61.2	.....	.....	.....
June	43.2	.....	11.4	.....	6.5 N	.....	58.4	.....	.....	.....
July	44.6	48.02	8.1	*	6.0 SW	.....	67.6	68.10	0.35	.....
Aug.	46.4	.....	8.4	16.3	5.2 SW	8.4 NE	45.8	.....	0.118	0.72
Sep.	43.2	39.84	7.97	14.0	4.4 E	.....	64.1	68.05	0.116	0.76
Oct.	30.0	23.40	6.6	8.3	8.5 E	.....	58.3	73.9	0.220	0.66
Nov.	24.7	14.13	4.9	5.9	9.5 E	8.55 NE	65.9	79.35	0.212	0.42
Dec.	18.6	15.43	4.9	8.2	9.4 E	10.5 NE	65.7	79.85	0.087	0.14
Average or total	26.5	28.16	7.46	10.54	7.41	9.15	57.7	73.85	1.103	2.70
1928										
Jan.	17.3	4.08	1.0	8.64	12.2 E	9.45 NE	54.9	81.75	0.121	0.25
Feb.	15.2	-2.01	6.68	7.93	10 E	6.8 NE	52.5	82.10	.....	0.22
Mar.	20.0	18.41	7.96	11.57	11.4 E	9.85 NE	56.4	68.35	0.071	0.27
Apr.	24.4	21.92	8.96	18.04	6.1 N	8.1 NW	61.4	66.55	0.040	0.08
May	37.0	41.35	9.7	18.8	5.5 SW	11.5 SE	64.2	71.55	0.103	0.18
June	47.5	51.95	12.2	12.5	5.6 W	8.48 E	60.2	65.61	0.069	0.159
July	....	50.26	*	17.6	5.4 W	7.43 E	....	75.4	.....	1.920
Aug.	....	49.84	....	16.8	10.6 E	9.05 E	....	78.37	.....	1.591
Sep.	....	41.42	....	13.4	15 N	7.75 E	....	78.01	.....	0.246
Oct.	....	26.94	....	8.1	8.6 E	6.7 NE	....	80.95	0.104	0.430
Nov.	....	15.28	....	6.5	7.4 E	8.15 NE	....	75.96	0.024	.....
Dec.	....	10.40	....	7.2	11.4 E	7.43 NE	....	89.0	.....	0.160
Average or total	26.9	27.49	7.75	12.26	9.10	8.39	58.3	76.13	0.532	5.506
1929										
Jan.	....	20.3	....	8.6	7.6 E	12.9 E	....	72.5	0.136	0.03
Feb.	....	11.52	....	8.4	11.2 E	8.71 E	....	87.0	.....	0.38
Mar.	....	18.23	....	11.5	10.6 E	9.7 NE	....	92.9	0.109	0.06
Apr.	....	25.79	....	13.9	6.7 E	8.99 E	....	83.0	0.033	0.13
May	....	38.88	....	19.3	6.4 N	9.85 NE	....	63.9	0.019	0.16
June	....	44.14	....	16.6	9.3 SW	11.18 N	....	63.1	0.041	0.92
July	....	51.58	....	15.9	4.8 N	10.15 E	....	72.8	0.138	0.689
Monthly average or total	....	30.06	....	13.46	8.09	10.21	....	76.46	0.476	2.369
Grand monthly average or mean total	28.33	28.57	7.34	12.09	8.40	9.25	56.13	75.48	1.333	5.517

* = incomplete.

there during the entire winter of October to March.

Reversed, as the storm travels, the trail of the snow-cover looks as in Table 11.

Table 11--Snow-cover, Inland Ice to the Sea, March 4 to April 7, 1928

Region	District	Water-content	Density
Coast Range	The seaside	6.41	31.5
	Head of the Fiord	5.52	31.4
	Center of Coast Range	6.81	33.4
	Mountain valley		
	Near center of Range	7.66	....
Plateau east of Coast Range	West side		
	Near Ikertok Fiord	1.70	29.5
	On Kangerdlugsuak	1.04	
	East side		
	Mt. Evans	0.62	25.8
Inland Ice	Lee slope at Ice-Front (compare with lee slope at Mt. Evans, 0.94 inch)	0.66	38.8
	On Inland Ice (western edge)	0.91	32.5

The trip lasted from March 4 to April 7, 1928. Consequently the Coast Range had accumulated somewhat since the surveys were ended in the east. However, the maximum gain did not exceed 1.04 inches in the west. The gain must have been far less in the east. The relative divergence remained practically unchanged.

The slight increase in snow-cover from Mount Evans onto the edge of the Inland Ice and the rising slope of the latter indicates an increased precipitation farther in.

The mean monthly evaporation and condensation are represented by stations and years in Table 12.

Table 13 sets forth the average monthly net rates of evaporation for snow, ice, water, and tundra. These are: Snow 1.394 inches; ice 0.800 inch; water 2.029 inches; tundra 0.568 inch. All are in terms of water.

The results on the Inland Ice (monthly net evaporation of snow 3.337 inches and ice 1.552 inches) confirms the vivid impression made by the foehn or stroph during our winter months on the Inland Ice. At that time we recorded in our diary that the Inland Ice was an unnatural mother who consumed her children of snow on the eve of giving birth to more. For the down draft was the harbinger of an approaching storm, which would probably replace what had been wasted. Furthermore, the evaporation on the edge of the Inland Ice, where we were camped, appeared to exceed greatly the actual precipitation. However, it is possible that the reverse is true near the crest, where the prevailing winds seem to be lighter. At least, the experience of Doctor Belknap and companions in the summer of 1933 indicated a zone of heavier wind midway between the edge and center of the Inland Ice. Such is the indication of the blowing down of their flags along their route. The evidence of Wegener's Expedition at Umanak has not yet reached the writer.

Later in the season the evaporation is greatly accelerated because of the moist ice and presence of pools. Thus even the strong warm foehns of winter may be exceeded in effectiveness by the milder winds of summer and the Sun which prevails practically the entire day through. At least melting at the Inland Ice edge exceeds accumulation, for there is no stratification shown by soil-marks in any of the crevasses or mühle.

Table 12--Evaporation, condensation, and meteorological elements in Greenland at stations on Arctic Circle

Year and Month	Temperature	Wind-velocity	Rel. humidity	Snow-pan		Ice-pan		Water-pan		Wind-velocity	Ice-pan		Water-pan	
				Evaporation	Condensation	Evaporation	Condensation	Evaporation	Condensation		Evaporation	Condensation	Evaporation	Condensation
	°F	mi/hr	o/o	inch	inch	inch	inch	inch	inch	mi/hr	inch	inch	inch	inch
				I--At Observatory, Mt. Evans							At Herz Lake			
1927														
Dec.	16.66	10.5	74.5	1.084	0.144	1.040	0.332	....	.....	....	.....	.....	.....	.....
1928														
May	41.5	12.42	70.9	.....	.....	.....	.....	2.34	0.129	....	.....	.....	.....	.....
June	51.96	8.47	65.6	.....	.....	.....	.....	4.60	0.038	2.91	.....	.....	3.840	0.038
July	50.2	7.4	75.4	.....	.....	.....	.....	4.90	0.180	3.84	.....	.....	2.520	0.168
Sep.	41.44	7.77	77.9	.....	.....	.....	.....	....	.....	....	.....	.....	0.684	0.236
Oct.	26.9	6.69	81.0	0.287	0.273	.....	.....	....	.....	....	0.438	0.219	.....	.....
Nov.	15.7	8.17	75.9	0.735	0.135	.....	.....	....	.....	....	0.408	0.021	.....	.....
Dec.	10.66	7.5	94.2	0.390	0.330	.....	.....	....	.....	....	0.204	0.144	.....	.....
1929														
Jan.	20.3	11.2	72.6	0.679	0.279	.....	.....	....	.....	....	0.870	0.038	.....	.....
Feb.	11.6	8.9	87.0	0.649	2.230	.....	.....	....	.....	....	0.540	0.138	.....	.....
Mar.	18.68	5.87	92.9	0.698	0.225	.....	.....	....	.....	....	0.372	0.150	.....	.....
Apr.	26.13	7.10	83.0	0.939	0.145	.....	.....	....	.....	....	0.435	0.012	.....	.....
May	38.86	9.85	63.8	.....	.....	.....	.....	2.88	0.3195	....	.....	.....	.....	.....
June	44.04	10.88	61.22	.....	.....	.....	.....	3.79	0.489	....	.....	.....	.....	.....
July	57.5	10.3	72.8	.....	.....	.....	.....	2.47	0.525	....	.....	.....	.....	.....
				II--Inland Ice										
1928														
Feb.	-2.85	9.2	89.9	1.297	0.369	1.131	0.447							
Mar.	22.6	9.75	72.5	5.745	0.000	2.469	0.049							
				III--At Holstensborg										
1928														
Apr.	24.3	6.00	62.7	1.442	0.016	0.54	0.24							
May	38.3	5.79	64.7	0.3945	0.978	.....	.....							

IV--Camp Michigan

Date	Tundra-pan		Water-pan	
Aug.18-Sep.2,1926	0.416	0.132	0.553	0.103
Equivalent 30 days*	0.832	0.264	1.106	0.206
Net balance	0.568		0.900	

*Mean temperature 42.6 F, mean wind-velocity 2.8 mi/hr, mean relative humidity 64.9 o/o.

The rates of evaporation with latitude will naturally be less where the down-slope winds do not prevail. In Scoresby Sound in the winter of 1891-92 a net mean monthly rate of only 0.163 inch for ice was reported. However, only the dimensions of the ice and their weights were given. An attempt has been made to compute the water-content. The accompanying notes of Table 14 refer to the rate of evaporation being increased at times by foehns. The search now should be for sectors where the wind may be strong but cold and, if possible, for sectors where comparative calm prevails. This should be the optimum spot for low evaporation. The writer offers Central Green-

Table 13--Monthly rates evaporation and condensation, in Central Greenland, 1926-1929

Station	Snow		Ice		Water		Tundra	
	Evaporation	Condensation	Evaporation	Condensation	Evaporation	Condensation	Evaporation	Condensation
	inch	inch	inch	inch	inch	inch	inch	inch
Camp Michigan (sea land), Aug.Sep.1926	......	......	......	......	-1.106	+0.206	-0.832	+0.264
	......	......	......	......	Net =	-0.900	Net =	-0.568
Mt. Evans (1200 feet) 1927-1928	-0.974	+0.379	-0.790	+0.286	.....	.....	.....	.....
	Net =	-0.595	Net =	-0.504	.....	.....	.....	.....
Mt. Evans (1200 feet) 1928-1929	-0.625	+0.374	-0.472	+0.103	-3.260[a)]	+0.274[a)]	.....	.....
	Net =	-0.251	Net =	-0.369	Net =	-2.986[a)]	.....	.....
					-2.348[b)]	+0.147[b)]		
					Net =	-2.201[b)]		
Inland Ice (1500 feet) Feb.Mar.1928	-3.522	+0.185	-1.800	+0.248	.....	.....	.....	.....
	Net =	-3.337	Net =	-1.552	.....	.....	.....	.....
Averages	-1.707	+0.313	-1.021	+0.212	-2.238	+0.209	-0.832	+0.264
Average net	-1.394		-0.809		-2.029		-0.568	
Scoresby Sound (sea land), winter 1891-1892 (Table 14), net = 0.163								

a)May to July 1928 and 1929 at crest. b)May to July 1928 and 1929 at Herz Lake below crest.

Table 14--Ice-evaporation at Scoresby Sound (latitude 73° north), October 1891 to January 1892

Kind of ice	Mean monthly evaporation
	inch
Glacier	0.134
Fiord	0.140
From Haven	0.212
From fresh-water lake	0.165

land as one portion of the mosaic of the picture when it shall have been completed. It is hoped that the data of Wegener's Expedition may furnish still another.

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APPENDIX A--MEASUREMENTS OF EVAPORATION AND TEMPERATURE FROM SOIL AND WATER IN SOUTHERN GREENLAND

J. E. Church

The following article is appended to the above discussion primarily because of the close relationship evident between the factors theoretically controlling evaporation and the evaporation as actually measured, and secondarily because it gives an insight into the temperature conditions of the soil and water upon which green Greenland, as distinct from white Greenland, exists.

I--Evaporation

The general thriftiness of the vegetation in Greenland despite the precipitation of approximately one inch per month then prevailing, caused the writer to inaugurate a series of experiments in evaporation in connection both with the tundra and open-water surfaces. The result shows that the evaporation during the two warmest months in an apparently dry summer exceeded but little, if any, the precipitation, thus leaving the winter accumulation of moisture in the humus and underlying blue-clay for purposes of growth or reserve.

The experiment was conducted with Mount Rose apparatus and methods used in studying the evaporation of snow, the pans being kept nested in the tundra to maintain the temperature of their contents at normal and weighed at such intervals as would represent differences in temperature, wind, and humidity. The main divisions were night and day with a few periods of 24 hours or longer. This would afford an opportunity to study the effects of night and day when they were growing slowly more diverse as the equinox approached and would show to a limited extent the relative potency of the factors of temperature, humidity, and wind. To simplify the comparison, the average hourly rate of evaporation is given,as well as the average temperature, humidity, and wind, in Table 1.

The evaporation of water would have been somewhat greater if the water-level could have been nearer the top of the pan. On the other hand, the evaporation from the tundra would have been less if rains caught by the pan had not raised the water-level higher than it normally exists in tundra.

Owing to the slight difference between the wind-movement at the pans and in Inner Greenland, the evaporation-factor obtained can be roughly applied elsewhere, except on the higher hills where the wind-movement, as indicated by that at Radio Point, is probably three times as great.

The comparison of evaporation-losses from open water-surfaces and from tundra is interesting because of the relatively small loss from the latter. Experiments by C. R. Ridgeway (Wyoming Exp. Sta. Bull. No. 52) indicates that the evaporation from soil with water-level six inches below soil surface is 95 per cent of that from a free water-surface, or if soil is kept loosened to the depth of six inches, the evaporation would be diminished 45 per cent or reduced to 54 per cent of that from a free water-surface. Yet in the present instance the soil protected by the thick mat of tundra has lost only 63.1 per cent including the amount transpired by the latter.

This shows vividly the xerophilous or "drought-loving" character of the arctic tundra, developed according to Schimper (Plant Geography) and Kihlman (Pflanzenbiologische Studien aus Russisch-Lappland) not from lack of precipitation but from impeded water-supply caused from the permanent presence of ice in the ground.

Major factors affecting evaporation--The factor of greatest potency appears to be the humidity, as shown in the evaporation of August 19 and September 1. For example:

	Humidity o/o	Wind mi/hr	Temp. air °F	Temp. water °F	Evaporation inch hourly
Aug. 19	70.1	6.7	51.3	48.0	0.0054
Sep. 1	39.5	5.3	47.9	45.0	0.0065

Table 1--Results measurements of evaporation, Camp Michigan, Greenland, August 18 to September 2, 1926

Date	Time	Length period	Wind end period		Humidity	Rain	Temperature				Evaporation			
			Direction	Movement			Air	Water in pan	Tundra in pan	Soil under pan	Tundra		Water	
											Total	Av. h'rly	Total	Av. h'rly
1926	h m	hrs		mi/hr	o/o	inch	°F	°F	°F	°F	o/o	o/o	o/o	o/o
Aug. 18	19													
19	6 20	11	N	1.3	74.0	....	46.8	....	......	4.5-in,39 6 -in,37	-0.001	0.0001	0.0005	0.00005
19	19 50	13.5	SW	6.7	70.1	....	51.3	48.0	......	......	-0.038	0.0029	-0.074	0.0054
20	7 30	12	E	1.1	85.2	....	42.2	44.2	2.5-in,46 4 -in,29.8	......	0.002	0.0002	-0.005	0.0004
21	19 00	35.5[a]	SW-S	4.2	72.0	0.08	43.8	....	......	......	0.130	Mostly rain	0.102	Mostly rain
22	19 15	24.3	W of S	2.5	67.9	....	41.6	45.0	......	......	-0.046	0.0019	-0.049	0.0020
23	9	14	SW	0.6	77.0	T	40.1	43.0	......	......	0.018	0.0013	0.026	0.0019
23	18 30	9.5	N-NE	1.7	53.8	....	50.0	47.0	......	......	-0.043[b]	0.0045	-0.031	0.0033
24	9	14.5	NE	3.0	63.3	....	37.6	32.0 frozen 3 mm	......	......	-0.017	0.0012	-0.024	0.0017
27	12	75	E to mostly W	2.8	68.1	0.33[c]	41.9	45.4	......	......	0.500	Mostly rain	0.404	Mostly rain
28	18	30	W of S	1.9	54.8	....	44.8	51.0	......	......	-0.082[b]	0.0027	-0.076	0.0025
29	18 15	24	SE	1.9	ca 50.6[d]	....	ca 43.7[d]	49.0	......	......	-0.052	0.0022	-0.064	0.0027
30	7 30	13	SE	1.2	64.2	....	37.6	32.0[e]	......	......	-0.0185	0.0014	-0.029	0.0022
30	18 40	11	NE	2.2	56.2	....	47.2	47.8	......	......	-0.0325	0.0030	-0.037	0.0034
31	7	12	E of S to N of S	1.5	67.5	....	36.3	Pan frozen 3 mm	......	......	-0.003	0.0003	-0.031	0.0026
31	19	12	E to NE	4.7	36.8	....	49.6	46	......	......	-0.034	0.0028	------	------
Sep. 1	7 30	12	E	2.9	56.0	....	38.3	33	......	......	-0.007	0.0006	-0.019	0.0016
1	18 30	11	E to S of E	5.3	39.5	....	47.9	45	......	......	-0.035	0.0032	-0.072	0.0065
2	6 10	12	N to E Gusty	4.7	55.0	....	38.5	30[f]	......	......	-0.007	0.0006	-0.042	0.0035
Totals or averages		14.4 days		2.8[g]	61.8	....	43.3	41.9	......	......	-0.416[h]	......	-0.553[i]	

[a] Rain-storm 2 days; snow on mountains. [b] Exceeds evaporation from water-surfaces since the rain (is this due to high water-level in pan?); has happened twice. [c] After 9^h August 25, total precipitation for storm probably 0.50 inch or even more; excess in water-pan is 0.404 inch over the evaporation for 75 hours. [d] Interpolated. [e] No ice in pan but ice in canvas bucket. [f] At surface 30°; at 1-inch depth 31°. [g] Wind on Radio Hill 6.9 mi/hr; wind in Inner Greenland 3.9 mi/hr. [h] Monthly total evaporation tundra, -0.866. [i] Monthly total evaporation water, -1.152.

Table 1A--Summary results Table 1

	Tundra	Water
Evaporation	-0.416	-0.553
Condensation (dew)	0.132	0.103
Net balance	-0.284	-0.450
Approximate equivalents 30 days	-0.568	-0.900

This is quite convincingly shown in the comparison of evaporation in Greenland and the Sierra Nevada later in this paper.

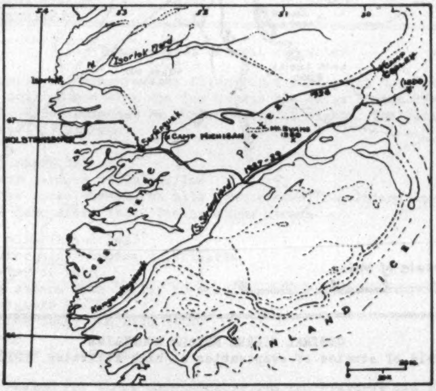
The factor second in potency is the wind, as is shown by comparing August 23 and 30 with August 19 above:

	Humidity o/o	Wind mi/hr	Temp. air °F	Temp. water °F	Evaporation inch hourly
Aug. 19	70.1	6.7	51.3	48.0	0.0054
23	53.8	1.7	50.0	47.0	0.0033
30	56.2	2.2	47.2	47.8	0.0034

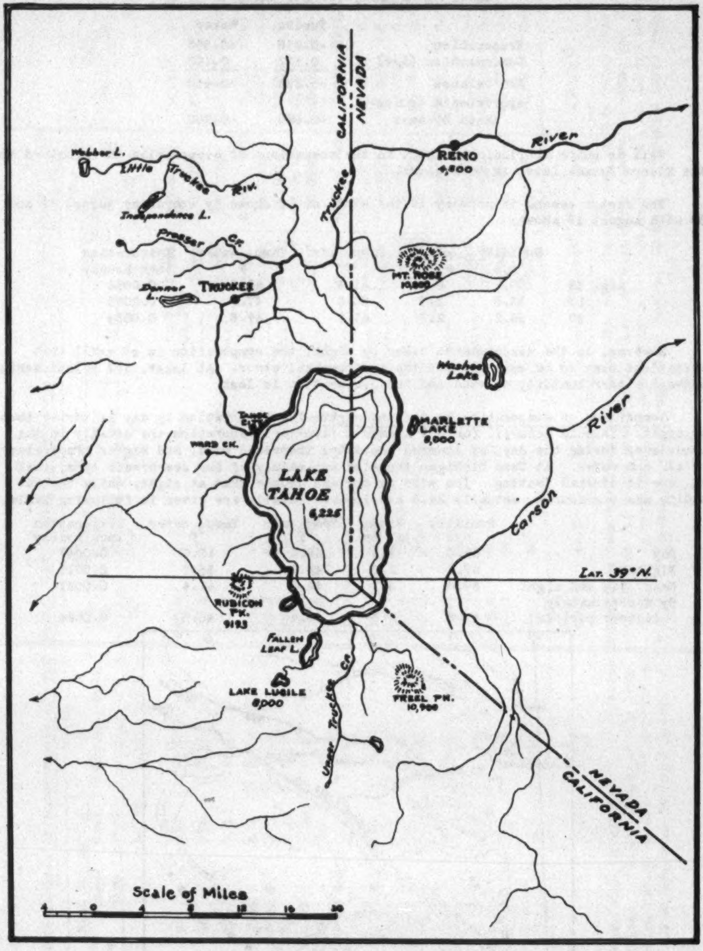
However, in the measurements taken by night, the evaporation is so small that variations seem to be smaller than the instrumental error. At least, all relationship between either humidity or wind and the evaporation is lost.

Comparison of evaporation by day and night--The evaporation by day is thrice that at night. This is natural, for all elements favoring evaporation are usually in the ascendency during the day, as lowered humidity, increased wind, and higher temperature of air and water. At Camp Michigan the wind was mainly of the sea-breeze type, that is, due to diurnal heating. The wind by day was double that at night, while the humidity was one-fourth, actually 24.3 o/o lower. Details are given in following table.

	Humidity o/o	Wind mi/hr	Temp. air °F	Temp. water °F	Evaporation inch hourly
Day	51.3	4.1	49.2	47.0	0.0047
Night	67.8	2.0	40.0	35.7	0.0015
Mean, day and night	59.6	3.1	44.6	41.4	0.0031
By approximately 24-hour periods	57.8	2.8	43.4	48.3	0.0024



CENTRAL GREENLAND
Field of studies of evaporation at high latitudes, 1926-29


Webber L.
Little Truckee Riv.
Independence L.
Prosser Cr.
Donner L.
TRUCKEE
Truckee
CALIFORNIA
NEVADA
RENO
4,500
River
MT. ROSE
10,800
Washoe Lake
MARLETTE LAKE
8,000
TAHOE CITY
WARD CK.
LAKE TAHOE
6,225
Carson River
LAT. 39° N.
RUBICON PK.
9193
FALLEN LEAF L.
LAKE LUCILE
8000
Upper Truckee Cr.
FREEL PK.
10,900
NEVADA
CALIFORNIA
Scale of Miles
4 0 4 8 12 16 20

CENTRAL SIERRA NEVADA MOUNTAINS
Field of studies of evaporation at high altitudes, 1910-17

Comparison of evaporation in Greenland and at eastern base of Sierra Nevada--Quite in keeping with the low temperature of air and water and the relatively high humidity is the low rate of evaporation found to exist, this being only one inch as compared with more than seven inches occurring the same month (August) at Lake Tahoe in the Sierra Nevada. All factors of evaporation are diverse except that of wind, the increase in the latter at Tahoe being only 0.4 mile per hour. For purposes of comparison the entire table of evaporation for August 1926 is given:

	Greenland	Sierra Nevada
Humidity, o/o	61.8	25.3 (Reno)
Temperature air, °F	43.3	60.0
Wind-movement, mi/hr	2.8	3.2
Evaporation, inch (approx.)		
Tundra	0.568	
Water	0.90	7.33 (water)

Comparison of ratios of precipitation to evaporation in Greenland and western United States--On the basis of measurements of precipitation and evaporation at Camp Michigan for the two weeks of August 20 to September 2 and measurements for the entire growing season in the western United States in 1887-88 (Carnegie Inst. Pub. 284, Tab. 15), the ratio of precipitation to evaporation in the former exceeds that at the following representative stations in the latter by from 17 to 410 per cent.

Station	Precipitation inch	Evaporation inch	Ratio o/o
Greenland			
Camp Michigan	0.650	0.553	117.5
Western United States			
Chicago	10.18	15.5	65.7
Des Moines	12.43	15.5	80.2
Topeka	13.95	13.9	100.4
North Platte	8.39	17.7	47.4
Denver	4.43	27.3	16.2
Santa Fe	6.11	31.9	19.2
Helena	3.87	20.4	19.0
Boise	1.22	25.8	47.3
Salt Lake City	2.09	28.8	7.3
Winnemucca, Nevada	0.98	33.6	2.9
Portland, Oregon	2.97	12.8	23.2
San Francisco	0.18	8.0	2.3

II--Temperatures of soil and water

(1) Water--A series of measurements inaugurated during the trip to the Inland Ice indicates that the soil rather than the Ice Cap is the cause of the low water-temperatures which prevail, aided somewhat by supercooling at night. The following measurements out of many will illustrate:

Water flowing from Inland Ice	°F
Water flowing over surface of Inland Ice	32.0
Water flowing over rocks one-fourth mile down stream from Inland Ice	42.0
Water in glacial lake (Lake Yost) fed by above stream	50.0
Waters unconnected with Inland Ice	
Lake Offield, water under tundra on hillside	36.0
Lake Offield, water in Lake	55.0
Semi-underground stream from Offley to Aussivigsuit Tasiat	46.0
Outlet of Aussivigsuit Tasiat	55.6
Tasersuak (25 miles long), in blue water	69.0
Camp Michigan, bog	33.0
Camp Michigan, Water Fall Creek	42.0

(2) Soil--The reason for these persistently low temperatures was traced to the eternal frost that exists even at the end of the season at the depth of 16 to 23 inches beneath the surface. The following observations, among others, were made at Camp

Michigan: July 10--Remnant of Inland Ice found at 6-inch depth under tundra; August 19--5.5 inches in humus above clay soil 42°.0 F, 7 inches in caly 36°.2 F, at 16 inches clear ice.

In northern Greenland, the frost-line is said to exist only one foot beneath the surface, while at Godthaab (200 miles south of Camp Michigan) the soil-temperature in August even at the depth of one meter (or more than twice that of the frost-line at Camp Michigan) is 12°.1 F above freezing.

Table 2 gives complete data for those who seek fuller details.

Table 2--Water- and soil-temperatures in °Fahrenheit, southern Greenland, 1926

(A) LAKES AND STREAMS	
Water flowing from inland ice	
On Inland Ice, surface-water, Aug. 7	32.0
One-fourth mile from Ice--flowing over rocks, Aug. 7	42.0
In glacial lake (Lake Yost) fed by above stream, Aug. 7	50.0
Waters unconnected with Inland Ice but affected by frost-line	
Lake Emmons (1 mile long)	
Aug. 2, 18^{h} (light breeze from across Lake)	56.0
Aug. 3, 7^{h} 15^{m} (minimum air-temperature, 31.0)	54.0
Aug. 9, 18^{h}	56.0
Lake Offley extension (near outlet Kardligsuit)	
Aug. 1, 18^{h}	53.0
Aug. 2, 6^{h} (minimum temperature, 32.6)	48.4
Lake Offley	
July 31, 11^{h} 50^{m}	59.0
July 31, 18^{h} (wind down Lake)	57.0
Aug. 1, 6^{h} (in shallow outlet 55; in tundra 1 foot beneath surface 36.0)	54.0
Aussivigsuit Tasiat (head of Lake, 10 miles long)	
July 30, 15^{h}, mountain stream flowing under tundra from Lake Offley (effect of low temperature of tundra, 36.0, noticed at Offley)	45.3
July 30, in bay at head of Lake (water partially landlocked)	59.0
Aussivigsuit Tasiat (foot of Lake)	
July 30, 10^{h} 15^{m} (breeze from east over Lake)	55.6
Little Aussivigsuit Tasiat (1 mile long)	
July 30, 10^{h} 15^{m}, in current of intake from large lake (intake short, temperature same as in large lake)	55.6
Little Aussivigsuit Tasiat (1 mile long, foot of Lake)	
July 29, 12^{h} (in calm shallows)	60.0
July 29, 18^{h} 15^{m} (wind from center of Lake all afternoon; does Lake serve as warming basin for colder waters of large Lake?)	58.0
Aug. 11, 15^{h} (only ripples on Lake)	62.5
Aug. 11, 18^{h}	60.3
Aug. 12, 6^{h} (minimum temperature, 41.0)	55.2
Tasersuak (20 miles long, head of Lake)	
July 26, 17^{h} (wind blowing up Lake since noon)	49.0
July 26, 21^{h} 15^{m} (wind still fresh)	45.5
July 27, 6^{h} 30^{m} (wind quieted)	47.0
July 27, 9^{h} 10^{m} (calm or rippling)	54.0
July 27, 9^{h} 20^{m} (in blue water, calm)	49.0
Aug. 12, 15^{h} (Lake stirred by wind)	55.0
Aug. 13, 6^{h} (calm, minimum air-temperature 43.0)	50.2
Aug. 13, 7^{h} 30^{m} (in blue water, breeze from west)	48.4
Tasersuak (near west or lower end)	
Aug. 14, 6^{h} (calm, minimum air-temperature 39.2)	49.0
Tasersuak (head of south arm)	
Aug. 14, 10^{h} 10^{m} (very shallow for long distance from shore)	53.0
Tasersuak (at gate)	
Aug. 14, 15^{h} (in deep water)	49.0

[Note: Upper Maligiak Fiord, the lower extension of this system of lakes, showed temperature of 52°.0 F and 51°.5 F on August 17 (see C); however, succeeding temperatures were lower.]

Table 2--Continued

(B) TUNDRA AND UNDERLYING SOIL	
(a) In wet tundra or bog	
July 21, Lake Offley (within tundra on hillside)	36.0
Aug. 19, Camp Little (in bog south of creek)	
(1) Very small bog-hole (water exposed to air)	
Surface	33.0
2 inches deep	33.0
3.5 to 5 inches deep	33.0
7 inches deep	33.0
(2) Water-hole 12 by 46 inches	
In shallow arm 1 inch deep	35.0
Sheltered and shaded 4 inches deep	33.0
Against clay-bottom 12 inches deep	33.0
(3) Check, in creek running over rocks	42.0
Aug. 27, head of Akugdlek (that is, middle arm—surface of bog above beach)	35.0
(b) In soil	
Aug. 19, Camp Little	
(1) West or flat exposure	
Base of shallow roots, 2 inches deep	49.0
In damp humus, 3.5 inches deep	43.9
In damp humus, 4 inches deep	41.2
In damp humus, 5.5 inches deep	39.0
Upper surface of clay-soil, 7 inches deep	35.2
In clay-soil, 12.5 inches deep	35.0
In clay-soil, 14 inches deep	32.4
(2) North exposure	
(a) In soil protected by tundra	
Just above clay-soil, 5.5 inches deep	42.0
On clay-soil, 7 inches deep	36.2
In clay (bulb of thermometer not cloth-covered), 9.5 inches deep	39.0
In clay, 11.5 inches deep	36.0
In clay (bulb of thermometer not cloth-covered), 15.5 inches deep	39.0
In clay, 17 inches deep	35.2
In clay, 20 inches deep	32.2
In clay, 23 inches deep	32.1 or 32.0[a]
(b) In exposed clay	
6.5 inches deep	41.6
13 inches deep	37.8
13.5 inches deep	38.4
(3) Clay-bank (steep west exposure)	
In moist soil, 21 inches deep	38.8
In chamber on solid(?) gravel or frost-line, 34 inches deep	34.0
(c) Digging for frost-line	
July 10, beneath tundra on brow of hill, 4 inches thin ice	
Aug. 19, beneath tundra	
(1) Drilling in clay 13.5 inches	34.2
18.5 inches	32.8
16.5 inches	32.8
18.5 inches	32.5
19 inches ("Moist, yet soil so firm that it bends drill when hammered down; so must be in a state of freezing; frost-line near here and insulated by tundra")	32.0
(2) Open hole	
In clay, 16 inches[a]; crystal clear ice interlarded in clay and upper surface near melting point; ice seemed to persist with depth at least 1 inch more and also farther as shown by drill	

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[a] The rise of the frost-line with increase in latitude is shown by the fact that in August at Godthaab (200 miles to the south) the frost-line is deeper than one meter, the soil-temperature at this point being 12°.1 F above freezing, while in northern Greenland the frost-line is said to exist only one foot beneath the surface.

Table 2--Continued

(C) FIORDS	
(a) Maligiak Fiord (north fork Ikertok)	
Aug. 17, off Belknap Island	52.0
Aug. 17, north head of University Bay	51.5
Aug. 24, south head of University Bay	42.0
Aug. 24, at Boat Landing Bay	45.0
Sep. 2, north point of University Bay (flood-tide afternoon)	45.6
Sep. 2, south point of University Bay (flood-tide afternoon)	45.6
Sep. 2, center of University Bay (flood-tide afternoon)	45.6
Sep. 2, west point of island in Bay (flood-tide, shallow)	46.1
Sep. 2, at tide-gage (flood-tide, shallow)	46.1
Sep. 3, at tide-gage (ebb-tide morning, air-temperature during night 28°)	45.0
Sep. 3, inner edge of Bay (ebb-tide, water calm)	45.0
Sep. 3, center of Bay (ebb-tide, water calm)	45.6
Sep. 3, south point of Bay (ebb-tide, water calm)	45.6
Sep. 3, anchorage (ebb-tide, water calm)	46.0
(b) Ikertok Fiord (main arm)	
Sep. 3, head (ebb-tide forenoon, water calm)	46.6
Sep. 3, one-third distance to Sarfanguak (tide rising, water calm)	47.0
Sep. 3, two-thirds distance to Sarfanguak (tide rising, water calm)	47.8
Sep. 3, off inlet to Sarfranguak (tide rising, water calm)	47.6
(c) Amerdlok Fiord	
Sep. 3, leaving Sarfanguak (tide near flood, afternoon)	44.0
Sep. 3, one-fifth distance to Holstensborg (tide near flood, afternoon)	43.6
Sep. 3, one-third distance to Holstensborg (tide near flood, wind fresh)	43.8
Sep. 3, one-half distance to Holstensborg (tide near flood, wind fresh)	44.0
Sep. 3, nearing the sea (tide near flood, wind fresh)	44.0
(d) Holstensborg Harbor	
Sep. 5, a.m., near shore (low tide, forenoon calm)	43.0
Sep. 5, a.m., middle harbor (low tide, forenoon calm)	43.0
Sep. 5, a.m., inside of entrance to sea (low tide, forenoon calm)	43.0
Sep. 5, p.m., near harbor mouth (tide higher, fresh wind from sea in afternoon)	43.0
Sep. 5, p.m., middle harbor (tide higher, fresh wind from sea in afternoon)	43.2
Sep. 5, p.m., near shore (tide higher, fresh wind from sea in afternoon)	43.4
(D) OCEAN (Davis Strait to Gulf of St. Lawrence)	
Sep. 8, Davis Strait, 200 miles south of Holstensborg	41.5
Sep. 9, Davis Strait, 275(?) miles south of Holstensborg	44.6
Sep. 9, working southwest toward Labrador, 340 miles south of Holstensborg	44.2
Sep. 10, working southwest toward Labrador, 500(?) miles south of Holstensborg	43.5
Sep. 10, working southwest toward Labrador, 500(?) miles south of Holstensborg (heavy wind and waves from northeast to east)	42.8
Sep. 11, south of Hudson Strait, 150 miles south of Cape Chidley (higher temperature due to close approach to shore, where land- and bay-water is warmer)	43.9
Sep. 11, 15^{h}, occasional icebergs, must be within 15 miles of shore (higher temperature due to close approach to shore, where land- and bay-water is warmer)	44.2
Sep. 12, 9^{h}, off Labrador Coast, but farther out	43.0
Sep. 12, $15^{h}\ 30^{m}$, off Labrador Coast (icebergs to starboard all day, some floating ice; air very chilly; sea becoming rough; is this Labrador Current?)	37.2
Sep. 13, $7^{h}\ 30^{m}$, off Labrador Coast (ten icebergs off starboard bow)	37.2
Sep. 13, 17^{h}, within sight of land, nearly off Easter Island outside Turnavik (icebergs in either side; jelly-fish thick on banks; almost calm)	38.7
Sep. 14, $8^{h}\ 20^{m}$, Cape Harrison on starboard stern	38.7
Sep. 14, $10^{h}\ 30^{m}$, entering inlet east of Indian Harbor	43.3
Sep. 14, $11^{h}\ 30^{m}$, between Cutthroat Point and Indian Harbor (inside of islands)	43.0
Sep. 14, $16^{h}\ 30^{m}$, in open sea off Sandwich Bay (in open sea; berg fragments in distance; air-temperature 42.8, in Sun 44.2)	42.8
Sep. 15, $8^{h}\ 30^{m}$, off Cape Bluff	45.0
Sep. 15, $17^{h}\ 20^{m}$, off Battle Harbor, nearing Belle Isle (a few icebergs still along shore and far out; one very large)	45.5
Sep. 16, $8^{h}\ 15^{m}$, inside Belle Isle Strait (one piece of ice)	45.3

Table 2--Concluded

(D) OCEAN--Concluded	
Sep. 16, 17^h, slightly farther in Strait (squall; several measurements made while rounding iceberg but no variation in water-temperature detected with Centigrade scale; was water mixed by squall?)	44.6
Sep. 17, 9^h 30^m, in harbor of Lance au Loup, 60 miles south of Belle Isle (nearly calm; fog; same temperature as Holstensborg)	43.0
Sep. 17, 17^h, in harbor of Lance au Loup (waves running in white caps)	42.8
Sep. 18, 9^h, in Gulf of St. Lawrence, 20 miles off Newfoundland (fog)	54.9
Sep. 18, 18^h, in Gulf near Point Rich	55.6

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WATER-LOSSES IN HIGH LATITUDES AND AT HIGH ELEVATIONS

Robert E. Horton[a]

Water-losses equal the difference between rainfall and runoff. Most determinations of runoff have been made in middle latitudes and at low to medium elevations above sea-level. Most of our factual knowledge of water-losses is limited to such regions. Knowledge of water-losses in high latitudes is of scientific importance in relation to problems of ecology and polar climatology. Knowledge of water-losses at high elevations is important in a variety of ways. The best and often the only economic use of high mountain areas is to supply water to lower regions. Knowledge of water-losses at high elevations is of scientific interest, for example, in relation to the perplexing problems of the alimentation of mountain glaciers and in relation to the ecology and zonal distribution of vegetation.

Water-losses may conveniently be divided, like all Gaul, into three parts: (1) Rainfall interception; (2) transpiration by vegetation; (3) evaporation from the soil. These are all evaporative in nature. Accordingly attention will be directed particularly to the variation of evaporative capacity with latitude and elevation. This involves some interesting and much-discussed problems: (1) Whether evaporation increases or decreases with elevation, other things equal; (2) whether there is or is not an appreciable increase in available water-supply by condensation in the cold climates at high latitudes and high elevations, particularly in the region of perpetual snow.

Transpiration, which is the principal type of water-loss in tropical and temperate climates, becomes of decreasing importance in high latitudes and high elevations as vegetation takes on more sparse, stunted, alpine or semi-xerophytic characteristics, until, to the north of or above the snow-line transpiration is nil or negligible and the only source of water-losses is direct evaporation from the snow-surfaces.

The transpiration-loss in different localities, while closely related to evaporative capacity, is not directly proportional thereto. The relationship may be expressed in the form

$$T = F(E_c)\,y \qquad (1)$$

where $F(E_c)$ is some direct function of the evaporation as measured, for example, by a standard Class A United States Weather Bureau evaporation-pan, and y is the annual production of dry matter by vegetation, per unit of area. The dry-matter production, y, other things equal, generally increases with rainfall. The rainfall, broadly speaking, generally increases with elevation and decreases as latitude increases, but these rules are often reversed locally. Whether water-losses (as distinguished from evaporation) increase or decrease with latitude and elevation depends on the conditions. Up to the snow-line there will be an increase only if the product of the two factors in equation (1) increases with latitude and elevation.

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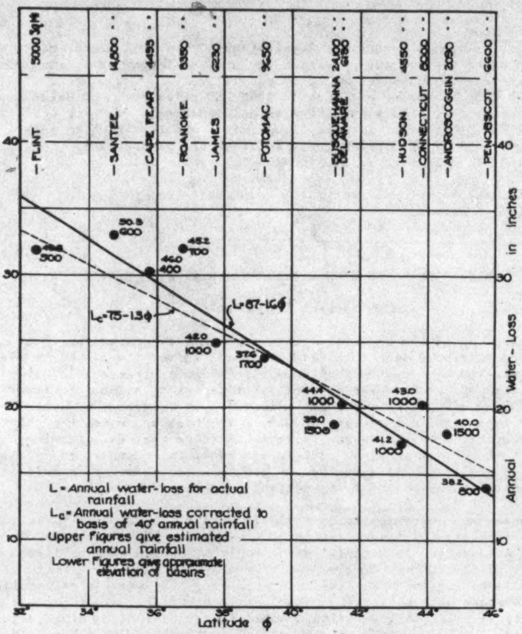


FIG.1-RELATION BETWEEN LATITUDE AND AVERAGE ANNUAL WATER-LOSS
ATLANTIC COAST BASINS

The subject is difficult and complex and the data are meager. Nothing more can be attempted in this paper than to outline by example and theory some of the disputed points, salient features, and unsolved problems.

Datum-line for water-losses

A scale of comparison has been provided, Figure 1, by plotting in terms of latitude the approximate water-losses from the drainage-basins of the principal streams entering the Atlantic Ocean in the United States. Figures adjacent to the plotted points show the approximate elevations of the drainage-basins. These average about 1000 feet above tide. The data used have not been reduced to a simultaneous time-interval and are approximate. The excellent agreement between the plotted points and the average line indicates that water-losses are closely related to latitude, and for the region under consideration there is a simple linear relationship, expressed by the equation

$$L = 87 - 1.6\,\varphi \qquad (2)$$

L being the annual water-loss in inches depth and φ the latitude. As this equation is empirical, it may not apply outside the range of latitudes 32° to 46° north covered by the data. It is interesting to note, however, that this equation indicates an annual water-loss of 87 inches at the equator and zero water-loss in latitude 54° north. It is to be noted, however, that the equation is based on conditions where transpiration by vegetation is the predominant loss. This loss becomes sensibly zero at some latitude considerably south of the pole but it does not follow that the total water-losses are zero at points farther north. There is a moderate but somewhat irregular variation in rainfall with latitude on the drainage-basins considered. In general the rainfall decreases as the latitude increases, averaging about 50 inches for the southern streams and 40 inches per annum for the most northerly drainage-basins.

A committee of the New England Water Works Association developed a formula for runoff in New England (Report of Committee on Yield of Drainage-Basins, J. N.E.W.W. Assoc., Dec. 1914, p. 541) in terms of rainfall. Converted into a formula for water-losses, this has been used to correct the data on Figure 1 to the basis of 40 inches rainfall. The corrected line is dotted. The formula is

$$L = 1.1 P - (P^2/100) + 6.27 \qquad (3)$$

The ratio of the water-losses for 40 inches rain to the losses for the actual precipitation was computed and the observed losses multiplied by this ratio were used to obtain the corrected line. Within moderate limits this formula may safely be used in conjunction with Figure 1 to determine the water-losses in different latitudes and near sea-level for rainfall differing from 40 inches.

Wagon Wheel Gap experiments

These include rainfall- and runoff-records on two drainage-basins on the east slope of the continental divide in Colorado, October 1910 to September 1926, inclusive. The drainage-basins have mean elevations slightly above 10,000 feet and are at latitude 37° 40' north. Drainage Basin A remained unchanged; Drainage Basin B was deforested in 1918 but quickly grew up to poplars and ground vegetation. The characteristics of the two drainage basins are shown by Table 1.

Table 1--Wagon Wheel Gap drainage-basins

Detail	Basin	
	A	B
Area, acres	222.5	200.4
Highest elevation, feet	11,355.	10,952.
Lowest elevation, feet	9,373.	9,245.
Mean elevation, feet	10,209.	10,133.
Average orientation of slopes	E 5° S	E 32° N
Vegetation		
Burned or barren, per cent	9.5	6.6
Grass, per cent	12.1	9.1
Aspen, fir, spruce, and pine, per cent	78.4	84.3
Mean slope, degrees	25.	21.
Mean temperature, degrees F	34.0	34.4
Mean rainfall, inches	21.09	20.97
Mean runoff, inches	6.14	6.68
Mean water-losses, inches	14.95	14.29
Mean snowfall, inches	122.7	.....

This experiment has been described by Bates and Henry (C. G. Bates and A. J. Henry, Stream-flow experiment at Wagon Wheel Gap, Colorado, preliminary report, M.W.R., suppl., No. 17, Washington, 1922; also Forest and stream-flow experiment at Wagon Wheel Gap, Colorado, final report, M.W.R., suppl., No. 30, Washington, 1928) and only a few data pertinent to the present problem will be given here. [The results of the experiments of Bates and Henry do not seem to have been either adequately presented or fully analyzed. Data of the elaborate snow-accumulation records which were kept have not been published; neither are daily rainfall- or runoff-data given. Without these it is impossible to determine the ground-water flow, to separate ground-water from surface-runoff, or to determine the net actual water-losses for individual periods. A more complete analysis and presentation of the data by the Runoff Committee of the Section of Hydrology or some other agency would seem appropriate.]

Five rain-gages were used, two near the foot of each basin, one on each slope, and a fifth station near the divide at the heads of the two basins. The daily rainfall on either basin was taken as the mean of the downstream gage showing the higher precipitation and the head-water gage. Nearly all precipitation occurred as snow for the period November to April. Snow usually began in October and finally disappeared early in May. Rainfall-distribution resembled that in northeastern United States, the maximum rainfall months being the midsummer thunder-storm months, the precipitation being more or less uniform throughout the remainder of the year. Fifty-six per cent of the total precipitation occurred in the six summer months, May to October, inclusive.

There was usually a runoff of about one-fourth inch per month in December, January, and February, which was derived almost wholly from antecedent ground-water storage, as the temperature seldom rose above 32° during these months.

Table 2 gives seasonal data for Basin A for the period of record. The average annual water-losses were 15.21 inches, with 21.32 inches rainfall. This compares with about 27 inches water-losses to be expected from 45 inches rainfall near sea-level in the same latitude. All or most of the difference in water-losses is evidently attributable to difference in rainfall.

Water-losses from drainage-basins on the east and west slopes of the continental divide

In addition to the Wagon Wheel Gap measurements there are available data for a number of drainage-basins at high elevations close to the continental divide in Colorado, some draining toward the east, others to the west. The locations of these drainage-basins, together with the adjacent rainfall-stations, are shown on Figure 2. The characteristics of the drainage-basins and the runoff- and water-loss data are given in Table 3. Drainage-basins included in this Table are all at elevations exceeding 9,000 feet. [Runoff-data prior to 1921 are given by Follansbee (W.S.P. No. 500, U.S.G.S.); in Table 3, subsequent records where available are included. In an earlier discussion of Follansbee's data by the author (E.N.R., Feb. 28, 1924, pp. 355-358, incl.) a table similar to Table 2 is given in which the conversion-factor, second-feet = 2 × acre-feet per day, was inadvertently transposed. The table was given in corrected form in a subsequent issue (E.N.R., March 20, 1924, p. 502). The present discussion supersedes the two papers above referred to.]

The topography, vegetation, and climate appurtenant to the drainage-basins shown on Figure 2 are nearly identical with the drainage-basins at Wagon Wheel Gap, already described, with the exception that in case of basins draining the west slope of the continental divide there is a marked difference in rainfall-distribution. Drainage-basins to the east of the continental divide receive around 56 per cent of their annual precipitation in the summer half-year. Adjacent basins draining the west slope have precipitation quite uniformly distributed throughout the year, with consequently a larger proportion of snowfall and much smaller proportion of rainfall in the midsummer months when water-losses are a maximum.

For the purpose of determining the precipitation on the drainage-basins shown on Figure 2, profile curves were plotted showing the relation of rainfall to elevation as given by records at available rainfall-stations in this locality for the east and west slopes, respectively. These rain profile-curves are given on Figure 3. Most of the drainage-basins are between latitudes 39° and 40° north. Using the rainfall as derived directly from the profile curves, as shown by column 14 of Table 3, the apparent water-losses for basins draining the west slope come out 0.1 inch, with an average rainfall of 24.8 inches, while for the east slope the apparent water-losses average 6.1 inches, with a rainfall of only 20.9 inches. Table 3 shows that the water-losses are apparently negative on two of the basins draining the west slope, where there is the greatest snowfall, and amount to but three or four inches per year on the west slope in some other cases.

There are two reasons for believing the measured precipitation for the winter

TABLE 2 - SEASONAL DATA FOR DRAINAGE-BASIN A WAGON WHEEL GAP EXPERIMENT (inches depth)

Year	Nov. - Apr.			May - Oct.			Year			Total Snowfall	Mean Winter Temp °F
	P	Y	L′	P	Y	L′	P	Y	L′		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1910-11	9.44 (a	1.92	7.52	17.83	4.34	13.49	27.27	6.26	21.01	97.6	23.6
11-12	8.08	2.17	5.91	11.36	5.64	5.72	19.44	7.81	11.63	112.5	19.7
12-13	5.54	2.17	3.37	11.53	2.56	8.97	17.07	4.73	12.34	96.9	20.0
13-14	8.92	1.78	7.14	14.99	3.87	11.12	23.91	5.65	18.26	116.1	21.9
14-15	8.81	1.64	7.17	9.32	3.68	5.64	18.13	5.32	12.81	112.0	21.2
1915-16	12.30	1.91	10.39	14.36	3.83	10.53	26.66	5.74	20.92	134.0	23.6
16-17	10.90	1.90	9.00	7.86	7.64	0.22 (d	18.76	9.54	9.22	149.7	19.6
17-18	7.53	1.49	6.04	12.24	1.62	10.62	19.77	3.11	16.66	80.7	25.8
1918-19	11.14	1.86	9.28	10.90	4.26	6.64	22.04	6.12	15.92	120.6	19.3
1919-20	11.96	1.55	10.41	12.02	6.36	5.66	23.98	7.91	16.07	170.5	20.9
20-21	8.02	1.98	6.04	11.99	4.92	7.07	20.01	6.90	13.11	133.0	21.6
21-22	10.82	1.81	9.01	10.47	5.01	5.46	21.29	6.82	14.47	151.1	21.2
22-23	11.53	1.83	9.70	14.79	4.33	10.46	26.32	6.16	20.16	148.3	20.6
23-24	9.41	2.40	7.01	6.42	4.63	1.79	15.83	7.03	8.80	127.5	20.1
24-25	8.46	1.99	6.47	14.33	2.24	12.09	22.79	4.23	18.56	99.2	22.0
1925-26	6.54	1.62	4.92	11.29 b	2.80 c	8.49	17.83	4.42	13.41	87.9	22.1
Av. 1910-19	9.18	1.87	7.31	12.26	4.16	8.10	21.45	6.03	15.42	113.34	21.6
" 1919-26	9.53	1.88	7.65	11.62	4.33	7.29	21.15	6.21	14.94	131.1	21.2
" 1910-26	9.34	1.88	7.46	11.98	4.23	7.75	21.32	6.11	15.21	121.1	21.4

a) Used Aver. 1910-19 for Nov. (1.16) and Dec. (1.34)
b) " " 1919-26 (1.88) for Oct. 1926
c) " " 1919-26 (3.16) " " "
d) Low apparent water-losses due to 5.02 inches precipitation in April which contributed to stream-flow in the summer period

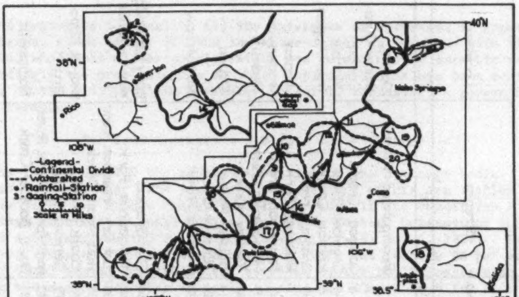

38°N
Silverton
Rico
108°W
Wagon Wheel Gap
Steamboat Springs
40°N
Gilman
11
12
10
19
20
Como
Alma
15
16
17
Twin Lakes
106°W
38°N
39°N
107°W
18
38.5°
106°
-Legend-
Continental Divide
Watershed
Rainfall-Station
Gaging-Station
0 5 10
Scale in Miles

FIG. 2 - DRAINAGE-BASINS ADJACENT TO CONTINENTAL DIVIDE IN COLORADO

TABLE 3 - YIELD OF COLORADO MOUNTAIN DRAINAGE-BASINS

No.	Stream	Location	Drainage Area Sq Mi	Percentage of Area above 9000 Ft	Approx. Mean Elevation Ft	Years Included		Number of Years	Orientation of Basin	East or West of Divide	Average Yield		Precipitation (Corrected for Elev.) Inches	Apparent Water-Losses L′	Corrected Precipitation P₁	Corrected Water-Loss L₁
						From	To				(a) C.S.M.	Inches				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1	Uncompahgre River	Ouray	44	94	10,500	1911	1924	14	N45°W	W	1.93	26.2	32.6	6.4	36.6	10.4
2	″ ″	Below Ouray	76	95	10,385	1913	1928	16	N45°W	W	2.19	28.7	31.9	2.2	35.8	6.1
3	Canyon Creek	Ouray	26	95	10,050	1911	1915	5	N70°E	W	2.46	33.4	29.9	-3.5	33.6	0.2
4	Crystal River	Marble	77	95	10,210	1917		1	N20°W	W	3.23	43.9	22.3	-21.6	25.1	-18.8
5	Maroon Creek	Near Aspen	42	95	10,205	1911	1916	6	N20°E	W	2.10	28.5	22.3	-6.2	25.1	-3.4
6	Castle Creek	″ ″	62	98	10,692	1913	1919	7	North	W	1.68	22.8	21.8	-1.0	24.5	1.7
7	Roaring Fork	Aspen	109	95	10,090	1912	1921	10	N70°W	W	1.70	23.1	21.9	-1.2	24.6	1.5
8	Fryingpan Creek	Thomasville	175	93	9,785	1914	1917	4	N40°W	W	1.51	20.5	21.3	0.8	24.0	3.5
9	Homestake Creek	Redcliff	64	98	10,405	1914	1918	5	N30°E	W	1.67	22.7	22.8	0.1	25.6	2.9
10	Turkey Creek	″	27	95	9,485	1914	1920	7	S75°W	W	1.23	16.7	20.8	4.1	23.4	6.7
11	Snake River	Dillon	92	99	10,740	1914	1919	6	West	W	.992	13.5	24.3	10.8	27.3	13.8
12	Tenmile Creek	″	113	98	10,420	1911	1919	9	N30°E	W	1.31	17.8	22.7	4.9	25.5	7.7
13	Fraser River	Near Arrow	28	100	11,165	1914	1930	17	N40°W	W	1.68	22.8	27.6	4.8	31.0	8.2
												24.7	24.8	0.1	27.8	3.1
14	Rio Grande	Thirty Mile Bridge	163	100	11,360	1914	1918	5	S75°E	E	1.51	20.5	32.0	11.5	35.5	15.0
15	Tennessee Fork	Near Leadville	45	100	10,460	1913	1918	6	S45°E	E	.862	11.7	18.4	6.7	20.4	8.7
16	East Fork Arkansas River	″ ″	52	100	10,955	1913	1918	6	S45°W	E	.822	11.2	23.0	11.8	25.5	14.3
17	Half Moon Creek	″ ″	26	100	10,707	1914		1	N45°E	E	1.21	16.5	20.3	3.8	22.5	6.0
18	Chalk Creek	Near St. Elmo	48	99	10,935	1914	1918	5	N70°E	E	1.06	14.4	22.8	8.4	25.3	10.9
19	Geneva Creek	Grant	74	99	10,740	1912	1917	6	S45°E	E	.993	13.5	20.8	6.3	23.1	9.6
20	North Fork-S. Platte River	″	51	92	9,850	1912	1917	6	S60°E	E	.650	8.8	15.2	6.4	16.9	8.1
21	South Boulder Creek	Rollinsville	39	94	9700	1911	1917	7	N80°E	E	1.63	22.1	14.8	-7.3	16.4	5.7
												14.8	20.9	6.1	23.2	8.4

a) C.S.M. - Cu Ft per Sec per Sq Mile

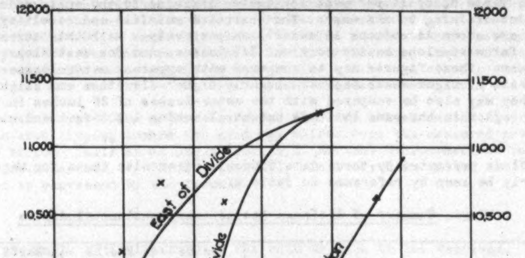


FIG. 3-RELATION BETWEEN ELEVATION AND AVERAGE ANNUAL PRECIPITATION FOR STATIONS IN VICINITY OF CONTINENTAL DIVIDE, STATE OF COLORADO

months in this region is too small: (1) The existence of instances of apparent negative water-losses, above cited; (2) the low water-losses as compared with the Wagon Wheel Gap data, where the winter precipitation was determined by snow-bin measurements. Accordingly the precipitation on these drainage-basins has been corrected by adding to the winter precipitation (November to April, inclusive) a percentage determined by the formula

$$\text{Per cent increase} = 1.5\ (\varphi - 35) + (H/500) \qquad (4)$$

where φ is the latitude and H the average elevation of the drainage-basin. This formula was derived by the author from snowboard observations at his own station near Voorheesville, New York, and from a comparison of the rainfall and runoff for winter conditions on eastern mountain drainage-basins (Robert E. Horton, Determining the mean precipitation on a drainage-basin, J. N.E.W.W. Assoc., v. 38, No. 1, 1924). For the drainage-basins shown on Figure 2 the correction comes out roundly 25 per cent. The percentage of total annual precipitation, as given by the published records, which occurred during the months November to April is close to 50 per cent for rainfall-stations on the west slope and 56 per cent for rainfall-stations on the east slope, shown on Table 3. Accordingly the rainfall derived from the profile curves has been corrected to allow for deficiency in catch of snowfall by increasing the quantity given

in column 14, Table 3, by 14 per cent for basins draining to the east, and 12.5 per cent for basins draining to the west. The corrected rainfall and resulting corrected water-losses are shown in columns 16 and 17, respectively. With this correction the water-losses for west-slope basins come out 3.1 inches, and for east-slope basins 8.4 inches per year. These figures may be compared with apparent water-losses of 14.96 inches for Basin A, Wagon Wheel Gap, at slightly higher elevation and slightly lower latitude. They may also be compared with the water-losses of 26 inches in the Atlantic coast region in the same latitude but at elevation 1,000 feet and with rainfall of 40 inches.

The problems presented by these data in conjunction with those for Wagon Wheel Gap may clearly be seen by reference to Table 4.

Table 4--Summary of drainage-basins near continental divide

Detail (1)	Basins draining west (2)	Basins draining east (3)	Basin A, Wagon Wheel Gap (4)
Number of basins......................	13	8	1
Mean elevation, feet..................	10,318	10,693	10,209
Corrected mean precipitation, P_1, inches	27.8	23.2	21.09[a]
Mean runoff, y, inches................	24.7	14.8	6.11[a]
Apparent water-losses, L'...............	3.1	8.4	14.96[a]
Apparent water-losses, L', omitting two negative values.....................	5.7	....	.....

[a] Minor variations in these quantities result from omission of third decimal in obtaining totals.

Columns 2 and 3 relate to 13 basins draining west and 8 basins draining east, gaged by the United States Geological Survey, column 4 to Basin A, draining east, at Wagon Wheel Gap. The mean elevations of the basins are nearly identical. The precipitation given in columns 2 and 3 has been corrected for deficiency in catch of the rain-gage. That given for Wagon Wheel Gap is as measured, using snow-bins in winter. The rainfall is slightly greater for the eight basins draining east than for Basin A. The runoff is more than twice as great and the apparent water-losses little more than half as great. The runoff records are apparently good. As most of these basins head on the continental divide, there is little danger of watershed leakage into the basins. Watershed leakage out of the basins is improbable, but if it occurred it would decrease the runoff and increase the apparent water-losses. Conditions as to watershed leakage are similar for the 13 basins draining west of the divide. Conditions for the eight basins draining to the east could be reconciled with Wagon Wheel Gap by an increase in precipitation. Probably the correction for deficiency of catch of snowfall as made is not large enough, as the deficiency tends to increase at higher elevations and with dryer snow, as shown by the observations by Cook (A. W. Cook, Comparison of rain-gage can and Horton snowboard at Grand Forks, North Dakota, M.W.R., Nov. 1924, p. 539).

Referring to the basins draining west, column 2, these have higher precipitation than the others, yet show much smaller apparent water-losses. Assuming that the measured runoff is substantially correct, the conclusion is inevitable that the actual water-supply is materially greater than that shown by the precipitation, even after correction for snow-catch deficiency. If the two basins draining west which show negative apparent water-losses are omitted, the result comes out 5.7 inches yearly apparent water-losses for the remaining basins. That the water-losses for the westward-draining basins should be less than for the eastward-draining basins is probable because the summer rainfall is larger and the heaviest rainfall occurs in July and August on the eastward-draining basins, when water-losses are a maximum. The rainfall on basins draining west is materially greater than on Basin A, and to reconcile the water-losses from the 13 basins draining west with that at Wagon Wheel Gap necessitates some new assumption.

The natural suggestion, and one often made in such cases, is that there is a large increase in available water-supply over the measured precipitation as the result of condensation at high elevations. This is negatived in the present instance by the fact that the five inner-cell evaporimeter records which were maintained continuously from 1920 to 1926 at Wagon Wheel Gap showed positive evaporation for every instrument and in every month. Furthermore, it could hardly be presumed that condensation would increase the available water-supply on some basins and not on others, such as Basin A, where all basins are similar in character and at the same elevation.

In a separate paper the author has shown that the actual amount of precipitation caught on an area sloping toward the wind may differ from the measured precipitation if the rain or snow falls at an angle (Robert E. Horton, Measurement of rainfall and snow, J. N.E.W.W. Assoc., v. 33, No. 1, 1919). This has been called the "roof-effect." The relation is expressed by the formula

$$\text{Actual catch}/\text{measured catch} = \cos (r - s)/\cos r \cos s \qquad (5)$$

where r is the angle of inclination of the rain or snow to the vertical, s is the slope of the surface in the direction toward the wind. These drainage-basins are all steep. For a slope of 30° and for snow falling at an angle of 45°, the actual winter precipitation, according to the above formula, would be 1.58 times the measured precipitation. This probably represents approximately the condition on the basins draining westward for the winter season. Such a correction would increase the available water-supply and hence the apparent water-losses for basins on the west slope by eight inches, giving apparent water-losses of 11 to 15 inches, in fair agreement with those obtained at Wagon Wheel Gap. Most of the precipitation on either slope is produced by winds blowing toward the divide; hence a similar correction is apparently required for basins draining east. This would reconcile these with the westward-draining basins as corrected and with Wagon Wheel Gap. If such a correction is required for the eight other basins draining east, apparently it should be made to the Wagon Wheel Gap basins. If applied there also, it brings the problem back about to where it started.

Winter water-losses and evaporation at Wagon Wheel Gap

The ground at Wagon Wheel Gap was almost invariably snow-covered continuously throughout the six months' winter season, November to April, inclusive. There was an average of 10.1 inches of snow on Basin A in October, much of which melted. Snow disappeared early in May. There was snow remaining May 1 apparently equivalent to something less than one inch of water, so that it may fairly be assumed that the snow-storage on the ground November 1 about balanced the snow-storage remaining on the ground May 1. Water-losses in the winter season are exclusively confined to evaporation from snow, and for the conditions described, with continuous snow-cover, it would be expected: (1) That the winter water-losses would measure approximately the evaporation from snow; (2) that there should be little or no correlation between the winter precipitation and the winter water-losses. On the contrary, the data show nearly a perfect correlation between apparent winter season water-losses and the winter season precipitation on Basin A. Referring to Figure 4, it will be seen that the apparent winter water-losses are very accurately represented by the linear equation

$$L' = P - 1.8 \qquad (6)$$

Of course the apparent water-losses include the gain or loss of ground-water and soil-moisture storage, but apparently the ground-water was at or close to its maximum on May 1 in most cases and the maximum ground-water storage was apparently somewhere from one to two inches. Allowing 1.0 to 1.5 inches gain in storage, the winter water-losses due to evaporation from snow on Basin A must be nearly equal to

$$L = P - 3 \qquad (7)$$

To find a correlation-coefficient close to unity between two sets of hydrologic data is almost unprecedented. It is still more surprising that this should occur in the present instance where, apparently, there should be little or no correlation. The condition described might result if there was a close correlation between winter temperature, the main factor controlling evaporation, and winter precipitation. Scatter diagrams plotted with reference to winter water-losses and winter temperature, precipitation, and summer water-losses, precipitation and yearly water-losses, for Basin A, show only slight or moderate correlation between any of these pairs of quantities. It is

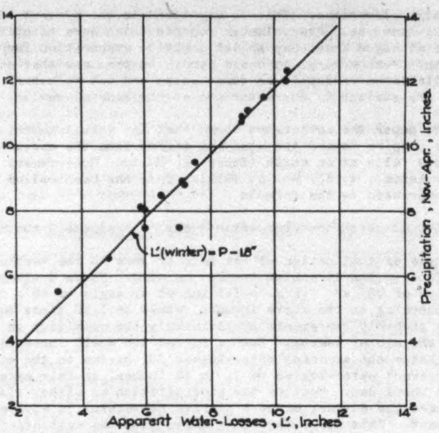


FIG. 4 - RELATION OF APPARENT WATER-LOSSES, NOV.-APR., TO PRECIPITATION BASIN A - WAGON WHEEL GAP EXPERIMENT

probable that the close correlation between winter water-losses and precipitation is due to interception of snow by tree-crowns. While the snow remains on the tree-crowns, the evaporation-surface and rate are both greatly increased. Usually the snow falls or is blown off from the tree-crowns or evaporated before the next snowfall. The amount of interception-loss is therefore nearly proportional to the number of storms. The number of snow-storms is in turn nearly proportional to the winter season precipitation. Whatever may be the explanation of this apparently anomalous situation, it appears certain that the winter seasonal evaporation from snow on Basin A, at something above 10,000 feet elevation, averages about six inches. This is of the same order as the winter water-losses on many forest-covered mountain drainage-basins in eastern United States at elevations around 1000 feet. Determinations of winter water-losses for these other basins may be and probably are too small because of deficiency in the measured precipitation due to the use of the ordinary rain-gage can to catch snowfall. So far the available data indicate that winter water-losses through evaporation from snow-surfaces do not increase and probably decrease with increased elevation.

It is of interest to compare the winter water-losses for Basin A with the evaporation. Two sets of evaporation-records were kept at Wagon Wheel Gap. In one set the evaporation was measured by means of Forest Service inner-cell evaporimeters. Records taken with these instruments were maintained continuously, summer and winter, at five stations during the period October 1919 to September 1926, inclusive. The evaporimeters were located at instrument stations A-1, A-2, B-1, B-2, and D. The average measured evaporation reduced to depth in inches as taken by these instruments is as shown by Table 5. It will be noted that there were large variations in the measured evaporation at different locations, particularly during the winter season.

Table 5--Average evaporation by inner-cell evaporimeters, Wagon Wheel Gap (depth in inches)

Period	Station					Average
	A-1	A-2	B-1	B-2	D	
Nov.-Apr.	0.98	1.89	1.88	2.19	2.11	1.81
May-Oct.	5.68	7.23	7.04	8.19	7.26	7.07
Nov.-Oct.	6.66	9.12	8.92	10.38	9.37	8.88

TABLE 6 EVAPORATION RECORDS AT U.S.W.B. CLASS A STATIONS

Station	Latitude	Elevation	Yrs. of Record	Yrs. Averagd	Evap. May-Oct Inches	Latitude factor for 40°	Equiv. Evap at Lat. 40°
Agricultural College, New Mexico	32° 00′	3863	13	13	55.95	1.31	42.7
" " , Bozeman, Montana	45 46	4900	13	13	34.91	.78	44.8
Alvarado, Calif.	37 36	5	7	7	37.81	1.09	34.7
Arrow Rock, Idaho.	43 30	3230	15	7	41.26	.86	48.0
Beeville, Tex.	28 25	225	10	10	38.71	1.45	26.7
Chapel Hill, N.C.	35 55	501	11	11	28.29	1.16	24.4
Chula Vista, Calif.	32 37	9	13	13	38.41	1.29	29.8
Clarksburg, W. Va.	39 16	1015	8	8	28.67	1.03	27.8
Columbia, No. 1 (West Campus), Mo.	38 57	738	11	11	27.92	1.04	26.8
" No. 2 (Expt. Sta.), Mo.	38 57		11	11	36.52	1.04	35.1
Columbus (Ohio State College) Ohio	40 00	757	12	8	25.78	1.00	25.8
Deer Flat, Idaho.	43 35	2510	9	2	35.41	.86	41.2
Dodgeland, Calif.	39 33	160	4	3	44.08	1.02	43.2
Dorchester Ctr., Mass.	42 20	100	2	1	16.83	.91	18.5
Elephant Butte Dam, N. Mex.	33 10	4265	15	15	64.37	.26	51.1
Dilley, Tex.	28 40	569	4	2	53.10	1.44	36.8
Fall River Hills, Calif.	41 01	3340	7	6	54.96	.96	57.2
Gardiner, Me.	44 15	163	10	7	25.26	.84	30.0
Hills Ranch (Austin), Tex.	30 14	475	16	16	43.69	1.37	31.9
Ithaca, N.Y.	42 27	890	13	11	23.55	.90	26.2
Jerome, Idaho	43 00	3888	9	6	35.79	.88	40.7
Lake Kachess, Wash.	47 16	2235	12	9	22.25[b]	.72	30.3
Lamoille, Nev.	40 45	6100	15	3	41.26	.97	42.5
Lee's Ferry, Ariz.	36 50	3143	11	10	65.53	1.12	58.5
Lincoln, Nebr.	40 49	1189	13	12	45.93	.98	46.9
Lahonton, Nev.	39 30	4200	7	3	47.75	1.02	46.8
Laredo, Tex.	27 30	421	3	2	71.05	1.48	48.0
Lawrence, Kans.	39 00	997	4	2	40.17	1.04	38.6
Los Griegos, N. Mex.	35 10	5200±	3	1	56.04	1.18	47.5
Malta, Mont.	48 25	2250	6	5	39.29	.68	57.8
Mesa Expt. Farm, Ariz.	32 25	1225	15	14	51.97	1.29	40.2
Milford, Utah.	38 30	4962	2	2	72.75	1.06	68.6
Milner Dam, Idaho	42 30	4200	5	5	40.85	.90	45.5
Myton, Utah	40 15	5030	13	5	47.39	.99	47.8
Manhattan, Kansas.	39 10	1100	5	4	42.30	1.03	41.1
Midlake, Utah	41 14	4235	4	3	64.83	.95	68.3

The second series of evaporation-measurements was made by the use of standard Class A United States Weather Bureau evaporation-pans, one located on the south slope and the other on the north slope of Basin A, at stations A-1 and A-2. Records of evaporation were obtained at these stations during the months June to October, inclusive, in the years 1920-26. If it may be assumed that the ratio of annual evaporation to that for the months June to October is the same for a Class A pan as for an inner-cell evaporimeter, then the annual and seasonal evaporation on the basis of Class A evaporation-pan measurements on Basin A can be determined as follows.

Average evaporation, June to September, 1920 to 1926, inclusive: North slope, Basin A, pan-measurement, 11.87 inches; south slope, Basin A, pan-measurement, 19.16 inches; average of the two, 15.51 inches; average evaporation at five stations determined by inner-cell evaporimeters for the same months and seasons, 5.21 inches; average yearly evaporation by inner-cell evaporimeters, 8.76 inches; ratio, annual evaporation to that for May to September = 8.76/5.21 = 1.68. Multiplying the pan-evaporation, June to September (15.51 inches), by this ratio gives 26.0 inches as the annual evaporation from a Class A pan at the Wagon Wheel Gap Experiment Station. The ratio of the evaporation by the inner-cell instruments for the winter period to the annual evaporation is 1.81/8.88 = 0.204. Multiplying the annual evaporation for Class A pans (26 inches) by 0.20 gives 5.20 inches as the winter season evaporation for a Class A pan

TABLE 6 EVAPORATION RECORDS AT U.S.W.B. CLASS A STATIONS
CONCLUDED

Station	Latitude	Elevation	Yrs. of Record	Yrs. Avertgd	Evap. May-Oct Inches	Latitude factor for 40°	Equiv. Evap. at Lat 40°
Nelson Reservoir, Mont.	48° 30′	2230	5	2	39.86	.67	59.6
Nephi, Utah	39 45	5300	2	1	40.21	1.01	39.8
North Platte, Sta. A, Nebr.	41 05	3000	13	11	39.30[a]	.96	41.0
" " " B, "	41 06	2825	13	7	37.50[a]	.96	39.1
Oakdale, Calif.	37 52	215	13	11	67.33	1.08	62.3
Pahrump, Nev.	36 14	2640	6	2	58.30	1.14	51.2
Pathfinder Dam, Wyo.	42 30	5735	5	3	48.65	.90	54.1
Piute Dam, Utah.	38 20	5900	13	10	54.02	1.06	51.0
Provo, Utah.	39 15	4532	8	8	33.66	1.03	32.7
Rapid City, S.D.	44 04	3251	2	2	34.99	.84	41.6
Roosevelt, Ariz.	33 45	2175	16	13	58.84	1.24	47.4
Salt Lake Airport, Utah.	40 45	4227	4	4	60.28	.97	62.2
Santa Fe Field, N. Mex.	35 41	7013	15	15	47.14	1.17	40.4
Shoshone Res. Dam, Wyo.	44 30	5385	3	1	34.96	.83	42.1
Sevier Bridge Dam, Utah	39 10	4980	10	1	53.66	1.03	52.1
Silverhill, Ala.	30 32	250	13	7	35.24	1.37	25.7
Spur, Texas	33 30	2300	10	9	43.55	1.25	34.9
Tribune, Kansas	38 30	3612	16	8	57.90	1.06	54.6
Utah Lake (Lehi), Utah.	40 25	4497	8	8	49.45	.98	50.4
Warm Springs, Ore.	43 40	1700±	5	1	55.00	.86	63.9
Valier, Mont.	48 20	3825	16	11	37.07	.68	54.5
Voorheesville, N.Y.	42 38	340	17	16	27.16	.90	30.2
Walla Walla, Wash.	46 02	1000	14	12	41.78	.77	54.4
Wichita, Kansas	37 41	1377	10	4	47.49	1.09	43.5
Willow Cr. Res., Gilman, Mont.	47 34	4414	4	3	26.33	.71	37.1
Willcox, Ariz.	32 00	4190	15	12	53.60	1.31	40.9
Wooster, Ohio	40 47	1030	13	10	23.84	.97	24.6
Yuma Citrus Sta., Ariz.	32 45	190	11	11	82.03	1.28	64.1
" Evap. " "	32 45	150	11	9	50.77	1.28	39.7

a) Apr.-Sept. average times 0.978 (0.978 is mean of ratios for adjacent stations of Apr.-Sept. average to May-Oct. average)

b) May-Sept. average times 1.069 (1.069 is mean of ratios for adjacent stations of May-Oct. average to May-Sept. average)

and 20.8 inches for the summer half-year. The water-loss coefficient, C_L, or ratio of water-losses to evaporation, is an index of the vegetational use of water. On the basis of these figures for evaporation and allowing 1.25 inches gain of storage in winter and an equal loss in summer (from Table 2)

$$C_L = (7.46 - 1.25)/5.20 = 1.20 \text{ for the winter half-year}$$
$$C_L = (7.75 + 1.25)/20.8 = 0.43 \text{ for the summer half-year}$$

Since the only winter water-loss is evaporation from snow, the first ratio should be about unity. [It may be greater than unity because of evaporation of intercepted snow from trees, as apparently occurred here.] The second coefficient is comparable with but less than its usual values near sea-level. A smaller coefficient is to be expected at Wagon Wheel Gap because of lower precipitation and less luxuriant and slower growing vegetation.

The preceding examples suffice to illustrate the difficulty of determining the relation of water-losses to latitude and elevation from data of precipitation and runoff at present available. The problem may also be attacked by determining the relation of evaporation to latitude and elevation and using this in conjunction with the water-loss coefficient. The determination of the water-loss coefficient requires either rainfall- and runoff-data or data regarding the character and density of vegetation and its water

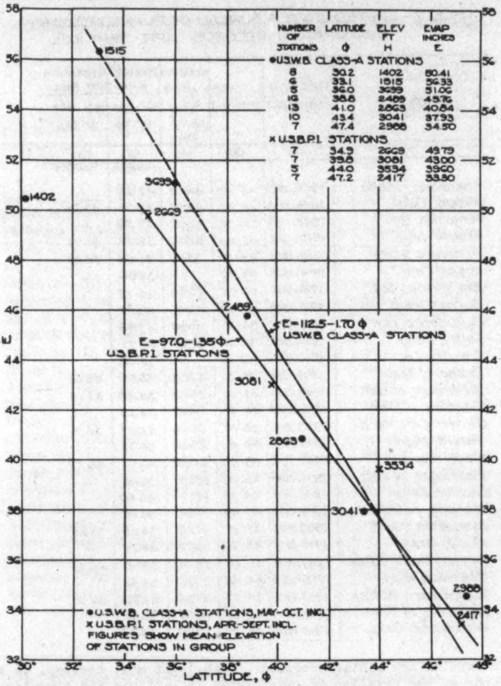
TABLE 7 - UNITED STATES BUREAU OF PLANT INDUSTRY EVAPORATION-RECORDS - APR.-SEPT. INCL.

Station	Record Available	Latitude (Approx)	Elevation above Sea-Level, Feet	Mean Evaporation Apr.-Sept. Incl.	
				1917-1931 15 Yrs.	1913-1932 20 Yrs.
(1)	(2)	(3)	(4)	(5)	(6)
				Inches	Inches
Aberdeen, Idaho	1913-1920	42° 40'	4400	42.20	-
Akron, Colo.	1909-1932	40 40	4650	43.73	43.53
Amarillo, Tex.	1908-1919	35 20	3676	47.89	-
Archer, Wyo.	1914-1932	41 00	6012	36.58	36.31
Ardmore, S.Dak.	1913-1932	43 20	3557	37.64	38.21
Biggs, Calif.	1916-1932	39 00	94	38.96	-
Big Springs, Tex.	1916-1932	32 00	2396	55.99	-
Burns, Oreg.	1914-1919	43 40	4125	39.52	-
Chillicothe, Tex.	1913-1931	34 20	1406	47.86	-
Colby, Kans.	1915-1932	39 30	3135	41.77	-
Crowley, La.	1910-1931	30 15	21	32.06	-
Dalhart, Tex.	1908-1932	36 20	4000	48.08	49.05
Dickinson, N.Dak.	1909-1932	47 00	2543	34.63	33.79
Edgeley, N.Dak.	1908-1920	46 20	1468	29.29	-
Garden City, Kans.	1908-1932	38 00	2836	54.67	54.16
Havre, Mont.	1916-1932	48 40	2505	35.32	-
Hays, Kans.	1907-1932	39 00	2000	46.01	46.27
Hettinger, N.Dak.	1911-1921	46 00	2253	32.42	-
Lawton, Okla.	1916-1932	34 35	1111	43.63	-
Mandan, N.Dak.	1914-1932	47 00	1750	34.18	-
Moccasin, Mont.	1909-1932	47 15	4228	34.28	33.98
Moro, Oreg.	1911-1931	45 40	1800	44.24	-
North Platte, Nebr.	1907-1932	41 20	2841	39.33	40.73
Sheridan, Wyo.	1917-1932	44 40	3790	34.42	-
Tucumcari, N.Mex.	1913-1932	35 30	4194	54.58	54.38
Williston, N.Dak.	1909-1918	48 00	1875	33.65	-
Woodward, Okla.	1914-1932	36 30	1900	50.45	-

requirement per unit of dry matter produced. Much light may, however, be thrown on the subject by a study of the relation of evaporation to latitude and elevation, since experience shows that, in general, water-losses do not exceed, except under special conditions, the evaporation from a water-surface.

Relation of evaporation to latitude at Class A United States Weather Bureau and at United States Bureau of Plant Industry evaporation-stations

Records of evaporation for the summer half-year, May to October, are available at 61 Class A evaporation-stations of the United States Weather Bureau for periods ranging from one to seventeen years at each station. The records average six years in length. The evaporation-pans used are four feet in diameter, ten inches deep, set above ground on grillage, and water is maintained in the pans to a depth of seven to eight inches. The pans are surrounded by fenced enclosures which, together with the instrument-shelters and other apparatus, afford considerable obstruction to wind-action. A summary of these records is given on Table 6. Records are also available for April to September at 27 stations of the United States Bureau of Plant Industry, as shown on Table 7. These records range from 6 to 25 years in length and comprise a total of 512 seasons or an average duration for each record of 19 years. The evaporation-pans used are six feet in diameter and 20 inches deep, buried in the ground to within four inches of the rim. [Prior to 1916 some pans were eight feet in diameter. No correction has been made for difference in size of pans. Comparison of 6-foot and 8-foot pans maintained side by side at Amarillo for nine years showed the evaporation from the 8-foot pan to be 97.75 per cent of that from the 6-foot pan.] Water is maintained at ground-level or four inches below the rim of the pan. The pans were freely exposed to the wind.



NUMBER OF STATIONS	LATITUDE ϕ	ELEV FT H	EVAP INCHES E
●U.S.W.B. CLASS-A STATIONS			
8	30.2	1402	50.41
6	33.1	1515	56.33
5	36.0	3699	51.06
16	38.8	2489	45.76
13	41.0	2863	40.84
10	43.4	3041	37.93
7	47.4	2988	34.50
×U.S.B.P.I. STATIONS			
7	34.9	2669	49.79
7	39.8	3081	43.00
5	44.0	3534	39.60
7	47.2	2417	33.50

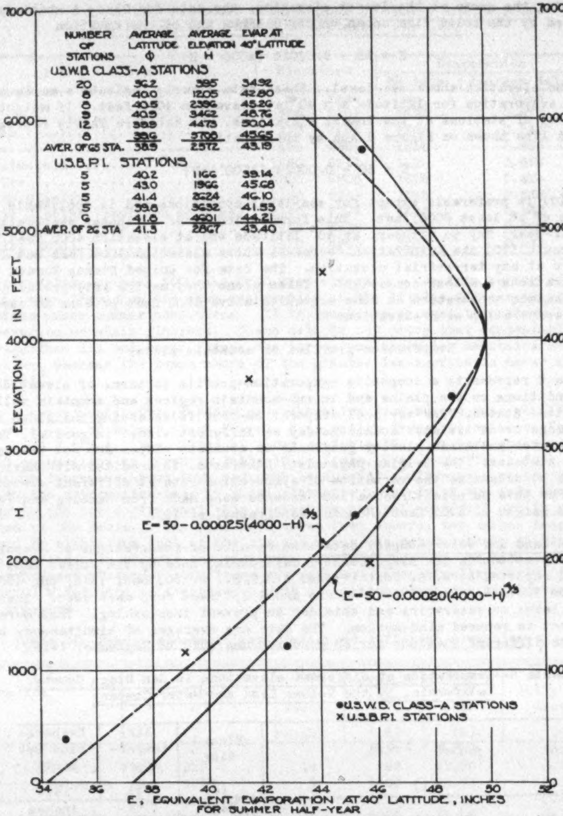
FIG.5-RELATION BETWEEN EVAPORATION AND LATITUDE

Group-means of the records were taken in terms of latitude for each set of records. Tables of the group-means and the plotted points derived therefrom are shown on Figure 5. The data are well represented by the lines shown on the diagrams and by the linear equations

$$\text{Class A, May-October............ } E = 112.5 - 1.70\ \varphi \qquad (8)$$

$$\text{U.S. B.P.I., April-September.... } E = 97.0 - 1.35\ \varphi \qquad (9)$$

The average elevation of the Class A stations is 2572 feet, that of the United States Bureau of Plant Industry stations, 2867 feet. Formulas (8) and (9) represent the evaporation-depth in inches as determined by the two types of pans and for the six-months' periods indicated at these respective elevations. The formulas may not apply outside of latitudes 30° north to 50° north. The relation of evaporation to latitude is probably not linear, especially near the poles. It is interesting to note, however, that formulas (8) and (9) indicate a summer season evaporation at the equator and at elevation about 2500 feet of about 100 inches and zero-evaporation at some latitude around 70°. [Reduced to elevation 1000 feet by the formula (10) given in the next paragraph, equation (8) becomes $E = 99.0 - 1.5\ \varphi$.] The last result is doubtful. That the evaporation by the two types of pans should not be the same is to be expected since the pans are not of the same size, the exposures to wind-action are different, the months covered by the records are not the same, and experience shows that the water-temperature in a buried pan and a pan set alongside it on grillage are not the same.



NUMBER OF STATIONS	AVERAGE LATITUDE ϕ	AVERAGE ELEVATION H	EVAP. AT 40° LATITUDE E
U.S.W.B. CLASS-A STATIONS			
20	36.2	395	34.92
8	40.0	1205	42.80
8	40.5	2396	45.26
9	40.9	3462	48.76
12	38.9	4473	50.04
8	39.6	5706	45.65
AVER. OF 65 STA.	38.9	2572	43.19
U.S.B.P.I. STATIONS			
5	40.2	1166	39.14
5	43.0	1966	45.68
5	41.4	2624	46.10
5	39.8	3632	41.53
6	41.6	4601	44.21
AVER. OF 26 STA	41.3	2867	43.40

FIG. 6-RELATION OF EQUIVALENT EVAPORATION AT LATITUDE 40° TO ELEVATION

Relation of evaporation to elevation at Class A United States Weather Bureau and at United States Bureau of Plant Industry evaporation-stations

Formulas (8) and (9) make it possible to correct the observed evaporation to the basis of a fixed latitude. Latitude 40° north was used as a datum. The observed evaporation at each station was multiplied by the ratio of the evaporation at the latitude of the station to the evaporation at latitude 40° as computed by equation (8) for Class A stations and as computed by equation (9) for United States Bureau of Plant Industry stations. Group-means of the resulting values representing evaporation at 40° latitude were taken in terms of elevation, and these data and the corresponding plotted points are shown on Figure 6. The data for Class A stations are consistent excepting for stations close to sea-level. The latter are subject to a marine climate as compared to the markedly continental climate appurtenant to the other stations.

Disregarding the group at the lowest elevation, the data for Class A stations are well represented by the solid line shown on the diagram and by the equation

$$E = 50 - 0.00020\ (4000 - H)^{4/3} \tag{10}$$

H being the elevation above sea-level. These data clearly indicate a maximum summer half-year evaporation for latitude $\varphi = 40^\circ$ at elevation 4000 feet. If weight is given to the group of stations at the lowest elevations, the data are fairly represented by the dotted line shown on Figure 6 and by the equation

$$E = 50 - 0.00025\ (4000 - H)^{4/3} \tag{11}$$

Formula (10) is preferable except for sea-level conditions and is applicable up to elevations of at least 6000 feet. This formula indicates 50 inches evaporation for the summer half-year, May to October, at 40° latitude and at elevation 4000 feet. According to formula (10) the evaporation decreases above elevation 4000 feet but does not become zero at any terrestrial elevation. The data for United States Bureau of Plant Industry stations are less consistent. Taken alone they may be interpreted as showing either a maximum evaporation at some elevation above 2000 feet or else no certain change of evaporation with elevation.

Evaporation-profiles on mountain slopes

Figure 6 represents a composite evaporation-profile in terms of elevation for average conditions on the plains and in sub-mountain regions and mountain valleys in western United States. The vertical evaporation-profile ascending the slope of a mountain range or on isolated mountains may be different since, in general, temperature lapse-rates and wind-velocity gradients on mountain slopes are not the same as on plains and plateaus. The Belgian physicist, Robertson, is credited with having made experiments to determine the variation of evaporation-rate at different elevations in 1903-04. For this purpose three balloon ascents were made from Hamburg and Petrograd, attaining a height of 8000 feet (McAdie, Aerography, p. 10).

Volcan Land and Water Company data--The results of observations of evaporation at different elevations in San Diego County, California, made by the Volcan Land and Water Company and reported by W. S. Post (Trans. A.S.C.E., v. 80, Dec. 1916, pp. 1906-1908), are shown on Table 8. Pans 3 feet square and 1 1/2 feet deep were used. These were floated on lakes or reservoirs and shielded to prevent insplashing. They were, therefore, subject to reduced wind-action. The data are averages of simultaneous observations at the different stations for 28 months, June 1913 to September 1915.

Table 8--Evaporation at different elevations in San Diego County, California, by the Volcan Land and Water Company

Station (1)	Elevation (2)	Air-temperature (3)	Evaporation per month (4)
	feet	°F	inches
La Mesa Reservoir, 5 miles from coast	480	67.3	5.85
San Luis Rey Creek	2620	57.5	4.88
Big Lake	2780	59.7	5.51
Cuyamaca Lake, 40 miles from coast	4620	54.5	6.64

Although the data show a uniform lapse-rate of air-temperature of 3° per 1000 feet, they do not show a consistent variation of evaporation with elevation, although they may be interpreted as showing a minimum evaporation at an elevation of about 2600 feet.

Maurer and Lütschg made a series of simultaneous observations of evaporation in the Swiss Alps, using porous-cup atmometers, for a period of 62 days, July 1 to September 1, 1920. Their results are given in Table 9. Disregarding Saas-Fee, at elevation 5906 feet, the data of Table 9 fall into three groups at average elevations 2400, 5200, and 7000 feet, respectively, and the mean evaporation at each elevation is practically the same. If Saas-Fee is included, the data may be interpreted as showing

Table 9--Porous-cup atmometer observations by Maurer and Lütschg in the Swiss Alps, July 1 to September 20, 1920

Station	Elevation		Evaporation	
			82 days	Average daily
	m	feet	mm	inch
Visp	656	2153	1395	0.670
Stalden	810	2658	1350	0.648
Balen	1490	4888	1330	0.638
Saas-Almagell	1680	5511	1410	0.677
Saas-Fee	1800	5906	1820	0.874
Allalin Glacier	2130	6991	1345	0.645
Allalin Glacier (southern moraine)	2140	7023	1420	0.681
Mattmark (Lake plain)	2109	6919	1250	0.600
Mattmark Hotel	2120	6955	1420	0.681

a maximum evaporation between 5000 and 6000 feet elevation. An interesting feature of these data is that they show the same evaporation at the Allalin Glacier as at the other locations under summer conditions. It is sometimes assumed that heavy condensation must occur on mountain glaciers. These data do not prove that condensation on the glacier-surface did not occur, since the porous-cup atmometer maintains nearly the air-temperature, whereas the temperature of the glacier ice-surface is never appreciably above 32[b].

Rohwer's experiments--Observations of evaporation from buried pans at different elevations were made by Rohwer (Carl Rohwer, Evaporation from free water-surfaces, Tech. Bull. 271, U.S.D.A., Dec. 1931) as shown on Table 10. [Rohwer concluded that the measured evaporation as given in Table 10 at Logan, Utah, and Pike's Peak, Colorado, should be increased about four per cent because of a difference in the brand of paint used on the evaporation-pans at these stations. A study of the data by the author leads to the conclusion that this correction was not justified and it has not been included in the Table.] The pans were three feet square, ten inches deep, buried in the ground to within one inch of the rim, and water was maintained to within one inch of the pan-rim. In general the pans were freely exposed to the wind. The observations represent midsummer conditions but were not taken simultaneously. They show in general a decrease of evaporation with increasing elevation and decreasing barometric pressure.

Table 10--Rohwer's data of evaporation at different elevations

Station (1)	Period (2)	Days of record (3)	Elevation (4)	Mean barometer (5)	Average daily evaporation (6)
			feet	inches	inch
Imperial, California	May, 1928	14	-68	29.86	0.384
Fort Calhoun, Nebraska	Sep., 1927	9	1160	28.77	0.174
Logan, Utah	June-July, 1928	14	4778	25.06	0.293
Ft. Collins, Colorado	Sep.-Oct., 1928	35	5000	25.02	0.149
Lake Tahoe, California	June, 1928	13	6300	23.76	0.222
Victor, Colorado	Aug., 1927	8	10089	20.80[a)]	0.170
Pike's Peak, Colorado	Aug., 1928	12	14109	18.07	0.149

[a)] Estimated.

The Mount Whitney evaporation-profile--The most complete and satisfactory determination of a mountain evaporation-profile is that taken by Frank Adams on the east slope of Mount Whitney, California, for the Office of Irrigation Investigations of the United States Department of Agriculture in the summer of 1904 (Samuel Fortier, Evaporation-losses in irrigation, Eng. News, Sep. 19, 1907, pp. 304-307). Tanks 22 inches in diameter and 28 inches deep were used, set in the soil. As shown on Figure 7, the results are consistent and indicate evaporation decreasing with elevation from 4000 feet to 10,000 feet, thereafter remaining nearly constant up to elevation 14,500 feet, at the summit of Mount Whitney. The observations do not extend below elevation 4000

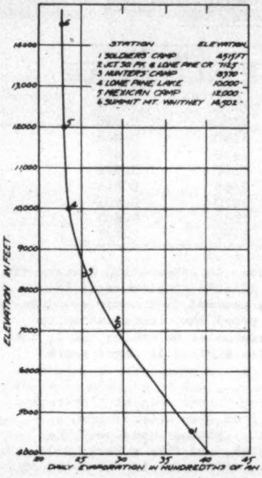


Fig. 7 - Influence of Elevation on Evaporation on East Slope of Mount Whitney

feet and so do not show whether a maximum evaporation-rate would have occurred at a lower elevation.

Taken altogether, the observational data described in the preceding paragraphs show: (1) A definite maximum evaporation for plains conditions at about elevation 4000 feet; for mountains, Adams' data show a decrease of evaporation with elevation on Mount Whitney, while Maurer and Lütschg's data show little evidence of variation in evaporation between elevations 2000 and 7000 feet in the Alps. Rohwer's data show an apparent decrease of evaporation in western mountain regions of the United States similar to that shown by the Mount Whitney profile. To determine if these various results can be reconciled they may be compared with vertical evaporation-profiles calculated for similar conditions. Before undertaking this it is necessary to consider the relation of latitude and elevation to the various factors controlling evaporation.

Variation of evaporation factors with latitude and elevation

Mean air-temperature--Hann has discussed at length the variation of air-temperature with elevation in mountain regions (Julius Hann, Handbook of climatology, Ward's translation). The following factors, which are in substantial agreement with Hann's results, have been tested for various localities in western United States (Table 11). These factors are not to be confused with the adiabatic lapse-rate for a non-saturated ascending air-mass, which is roundly 1° C per 100 meters or 1°F per 188 feet. Variation of air-temperature with latitude is also fully discussed by Hann and it has been shown that the mean air-temperature at a given parallel of latitude for the Earth's surface as a whole can be quite accurately expressed as a function of latitude and percentage of land-area, as has been done, for example, in the formula of Forbes

Table 11--Average air-temperature gradients, C

	m/°C	feet/°F
Plains, year.......	250	455
Hills, year........	200	364
Mountains, year....	183	333
Summer half-year	160	289
Winter half-year	206	376

$$\theta = -10.8 + 32.9 \cos^{5/4} \varphi + 21.2\, n \cos 2\varphi \qquad (12)$$

where n is the percentage of land on the given parallel of latitude. For determining an evaporation-profile what is required is the variation in temperature on the land along a given parallel of longitude or per degree difference of latitude. Hann's investigation (loc. cit.) shows that within the limits of the United States or between latitudes 30° and 50°, the variation of air-temperature with latitude is approximately 1.8° F per degree and this result is confirmed by temperature-maps of the United States. Using this and values of the vertical temperature lapse-rate, above given, the relation of temperature at a given station to that at a base-station can be represented approximately by the formula

$$\theta = \theta_b + 1.8\,(\varphi_b - \varphi) + (H_b - H)/C \qquad (13)$$

The subscript b applies to quantities relating to the base-station; θ and θ_b are mean temperatures at latitudes φ and φ_b; C is the surface-temperature lapse-rate (Table 11).

Water surface-temperatures--It is water surface-temperature rather than air-temperature which primarily governs the rate of vapor-emission and hence the evaporation-rate. The temperature of a water-surface in a lake, a river, or an evaporation-pan is not the same as the air-temperature. The departure is a function of the latitude and elevation. Records of water surface-temperature were kept prior to 1916 at most of the United States Bureau of Plant Industry evaporation-stations and from these data the following empirical formula for the departure Δ in degrees Fahrenheit of water-surface from air-temperature, where H is elevation above sea-level, has been derived

$$\Delta = 0.286\ (\varphi - 42.6) + 0.45\ H/1000 \qquad (14)$$

This relates to buried evaporation-pans four feet in diameter and 20 inches deep, the departure Δ being positive when the water is warmer than the air. A similar formula has been derived from such data as are available for United States Geological Survey 3-foot square pans, buried in the soil

$$\Delta = 0.383\ (\varphi - 36) + 0.45\ H/1000 \qquad (15)$$

and for United States Weather Bureau standard Class A evaporation-pans, four feet in diameter, set on grillage

$$\Delta = 0.55\ (\varphi - 35.2) + 0.45\ H/1000 \qquad (16)$$

The last two formulas are tentative. All three formulas indicate that water in an evaporation-pan at sea-level is warmer than the air near the equator, the difference becoming zero at a latitude ranging from 35° to 42°, depending on the depth of pan. For latitudes farther north the water surface-temperature is lower than the air-temperature at sea-level. As the elevation increases, the temperature of the water relative to that of the air increases. In middle latitudes, where air- and water-temperatures are practically equal at sea-level, the water becomes progressively warmer than the air at the rate of about 0°.45 F per 1000 feet. If, therefore, the air-temperature gradient is, for example, 3° per 1000 feet, the water surface-temperature gradient in an evaporation-pan will be about 2°.55 per 1000 feet. As far as available data permit any definite conclusion to be drawn, there appear to be somewhat similar relations between the air-temperature and water surface-temperatures in lakes and rivers, on the one hand, and latitude and elevation, on the other hand.

Vapor-pressure--Hann has given the following generally accepted formula for the relation between vapor-pressures V_H and v_o at stations separated by a difference of elevation H:

$$V_H/v_o = 10^{-H/6300} \qquad (17)$$

for H in meters. For H in feet this may be written

$$V_H/v_o = \varepsilon^{-H/9084} \qquad (18)$$

It has been shown by Angström that the variation of vapor-pressure with latitude is quite accurately represented by the formula

$$v = 1.6 + 17.0 \cos^3 \varphi \qquad (19)$$

where v is the vapor-pressure in millimeters (Anders Angström, Evaporation and precipitation at various latitudes, Arch. Math. Astr. Physik., Stockholm, 1925, v. 19-A, No. 20).

Wind-velocity--A map of ground wind-velocity at a height two feet above ground has been plotted for the western half of the United States from records of wind-velocity kept at Class A and United States Bureau of Plant Industry evaporation-stations, already referred to. This map shows that the isanemones run nearly north and south and there is no evidence of an appreciable change of wind-velocity with latitude in this region. The same data, analyzed with reference to elevation, are shown on Table 12.

Table 12--Relation between elevation and wind-velocity two feet above ground-level for the period May to October, inclusive, for conditions as within Class A evaporation-station enclosures

Limits of group-elevation (1)	Mean elevation (2)	Mean wind-velocity (3)	Number of stations in group (4)
feet	feet	mi/hr	
Less than 1000	351	2.38	22
1000 to 2000	1396	2.57	13
2000 to 3000	2449	3.16	14
3000 to 4000	3522	2.96	11
Greater than 4000	5021	2.97	21

A comparison of wind-velocities at Class A and United States Bureau of Plant Industry stations, the latter having free exposures, shows that wind-velocity two feet above ground, with free exposure, is 2.17 times that in instrument enclosures. Table 12 shows that there is a small increase of wind-velocity with elevation up to 2000 feet, with little change at higher elevations. This relates to conditions over plains. On mountain slopes the conditions more closely resemble those in the free air and the wind-velocity generally increases with elevation.

Relation of evaporation-coefficient to barometric pressure and elevation--It has sometimes been assumed that because water boils at lower temperatures as elevation increases and barometric pressure decreases, there must be an increase in the amount of evaporation with increased elevation. It is necessary to keep in mind the distinction between the relation of barometric pressure to the evaporation-coefficient and its relation to the evaporation-rate. Variation in the evaporation-rate with elevation is governed by the balance between all the factors affecting evaporation, including those already described, and variation, if any occurs, in the evaporation-coefficient. Even though the evaporation-coefficient increases with increased elevation there still may be a decrease in the evaporation-rate with increased elevation, under suitable conditions.

In 1862, Thomas Tate concluded that the evaporation-rate was inversely proportional to the atmospheric pressure. Stephan (1881) deduced the theoretical formula for evaporation by diffusion from a circular water-surface

$$E = r\delta \log_e (B - v)/(B - V) \tag{20}$$

where δ is the coefficient of diffusion and r is the radius of the water-surface. For small values of V and v, relative to B, this becomes, approximately

$$E = (4\, r\delta /B)(V - v) \tag{21}$$

This indicates that for vapor-removal by diffusion only, the evaporation-rate at different elevations varies approximately in the inverse ratio of the barometric pressure. Many evaporation-formulas include a factor for barometric pressure of the form

$$F(B) = B_o/B$$

This is applied directly to the Dalton vapor-pressure difference term (V - v), to which is also applied a wind factor F(w). Such formulas are generally of the type

$$E = F(B)\ (V - v)\ F(w) \tag{22}$$

the usual form being

$$E = C(B_o/B)(V - v)\ (1 + kw) \tag{23}$$

It is well known that the maximum vapor-pressure V at a given temperature is practically dependent on absolute temperature and on nothing else. It can be shown that the work required to transport a molecule from within a liquid to the limit of attractive return above the surface is one-half that required to transport it to an infinite distance against the resistance of the surface-attraction of the liquid and the pressure of the overlying air (Risteen, Molecules and molecular phenomena). The latent heat of vaporization represents the work necessary to transport a unit mass of the liquid from the interior of the liquid body to a distance remote from the surface. It comprises two elements: (1) Internal work in overcoming molecular attractive forces which, in general, including viscosity and surface-tension, increase as the temperature decreases, and the latent heat of internal work also increases as the temperature decreases; (2) the external latent heat, which measures the work done by the emitted vapor in expanding against the external pressure, decreases slightly as the pressure on the liquid surface decreases with decreased boiling temperature, but the total latent heat increases slowly as the temperature decreases.

Accordingly, the rate of vapor-emission at a given temperature should decrease slightly as the elevation increases or the barometric pressure decreases. The variation is so small as to be practically negligible and the rate of vapor-emission may be considered as nearly independent of the pressure on the liquid surface at a given temperature. It appears, therefore, that the variation in the evaporation-coefficient with varying barometric pressure must be ascribed chiefly to variation in the rate of vapor removal.

Vapor removal takes place by three processes: Diffusion, convection, and wind-action. Even if vapor removal by diffusion varies inversely as the barometric pressure, it does not follow that the evaporation-coefficient will vary in the same way unless it can be shown that vapor removal by the other two processes also varies in the same manner. This apparently is not the case.

In a mixture of air and water-vapor there is a certain number of vapor molecules per unit volume. When there is wind the air and vapor are swept along together at a rate depending on the pressure-gradient. This, as in case of hydraulic flow, is independent of the total pressure. At a given vapor-pressure the same amount of vapor is carried by the wind per unit of time and per unit of volume of air, whether the number of air molecules per unit volume is large or small. From this viewpoint it does not appear that variation in barometric pressure or, in other words, variation in elevation, should have any material effect on that part of the evaporation-loss from a water surface which is due to mechanical action of the wind, other things being equal.

From these considerations it seems certain that reduction in barometric pressure cannot increase and may somewhat decrease the rate of vapor removal by mechanical action of the wind. The relation of barometric pressure to convective vapor removal has apparently not been studied. Since convection is, in general, not present when there is strong wind-action, it will not be considered here. It is evident that in order to determine the effect of change in barometric pressure on evaporation, other things equal, its effect on vapor removal by diffusion, which is always present, and its effect on vapor removal by wind-action, must be considered separately. This may readily be accomplished by the use of an evaporation formula published some years ago by the author (Robert E. Horton, A new evaporation formula developed, E.N.R., v. 78, April 26, 1917, pp. 196-199)

$$E = C\,(\psi V - v) \qquad (24)$$

In this formula, V and v are the maximum and actual vapor-pressures, respectively; ψ is a wind-factor, based on the assumption that mechanical removal of vapor by the wind is of the nature of an exhaustion process and hence follows the inverse exponential or inverse compound interest law. It is also based on the assumption that the maximum possible effect of wind-action is to remove the newly emitted vapor from contiguity with the water-surface as fast as it is emitted.

$$\psi = (2 - \epsilon^{-0.2w}) \qquad (25)$$

where w is the wind-velocity, in miles per hour, and ϵ is the base of the Napierian system of logarithms. The value of ψ varies from 1.0 for still air, or w = 0, to 2.0 for an infinite wind-velocity. For still air the author's formula reduces to identity with the Dalton formula

$$E = C\,(V - v) \qquad (26)$$

for the same conditions. The constants in the author's formula were derived with reference to a standard Class A, 4-foot diameter, United States Weather Bureau evaporation-pan, on grillage, and the formula applies primarily to such pans near sea-level. For these conditions and for E expressed in inches per 24 hours, C = 0.40. This formula has been well verified by the experiments of Rohwer. It gives results nearly identical with those given by Fitzgerald's and Rohwer's formulas under ordinary conditions but differs from these and other existing formulas for extremely high wind-velocities. It leads to the result that the evaporation-rate does not approach infinity as the wind-velocity increases, other things equal, but approaches a maximum or limiting value dependent on the conditions. This must necessarily be so, for the reason that at a given water surface-temperature the evaporation-rate cannot exceed the rate of vapor-emission.

Equation (24) may be written

$$E = C\ (V - v) + C\ (1 - \varepsilon^{-kw})\ V \tag{27}$$

The first term represents evaporation by diffusion, the second, vapor removal by wind-action. Since redumtion in barometric pressure apparently increases the rates of vapor removal and vapor return by diffusion in the same proportion, it appears that the evaporation-coefficient for that part of the evaporation which results from diffusion should vary inversely as the barometric pressure, since the rate of diffusion varies inversely as the barometric pressure. If the effect of barometric pressure on wind-action is negligible, then introducing an inverse barometric factor in the diffusion term gives

$$E = C\ (B_0/B)\ (V - v) + C\ (1 - \varepsilon^{-kw})\ V \tag{28}$$

The relation of the evaporation with standard barometric pressure 29.9 inches to that with a barometric pressure B, other things equal, is given by the equation

$$E/E_0 = [(29.9/B)\ (1 - h) + (\psi - 1)]/[(1 - h) + (\psi - 1)] \tag{29}$$

where h is the relative humidity. This indicates that the effect of varying barometric pressure on the evaporation-coefficient, other things equal, is not a simple function of barometric pressure alone, as has heretofore been assumed, but that the effect varies with the wind-velocity and relative humidity.

Carpenter (L. G. Carpenter, Loss of water from reservoirs by seepage and evaporation, Bull. 45, Colo. Agric. Exp. Sta., Fort Collins, Colo., pp. 27-31) has given a formula for the evaporation-coefficient relative to that at 5000 feet elevation or with barometric pressure 25 inches

$$E/E_{25} = 1 + 0.04\ (25 - B) \tag{30}$$

This is apparently intended to be an approximate linear equivalent of the inverse barometric pressure rule for rate of diffusion.

Rohwer (op. cit.) carried out a series of experiments to determine the relation of the evaporation-coefficient to barometric pressure. The stations are listed and the periods of observation given in Table 10. Table 13 gives the averages of the meteorological factors governing evaporation during the period of observation at each station. From these data Rohwer derived the formula

$$E/E_{25} = 1.439 - 0.0186\ B \tag{31}$$

This is intended to give the ratio of the evaporation-coefficient C at a point where the barometric pressure is B relative to that for a barometric pressure of 25 inches.

For the purpose of comparison the relative evaporation for different barometric pressures has been calculated as shown on Table 14. The relation of barometric pressure to elevation varies, as shown by hypsometric tables, with temperature and humidity. The relation is, however, so nearly constant in middle latitudes that for practical purposes the elevations corresponding to different barometric pressures may be assumed to be as shown in column 2 of Table 14.

Table 13--Data of Rohwer's experiments on relation of barometric pressure to evaporation-coefficient

Station (1)	Elevation (2)	B (3)	Temperature: Air θ_a (4)	Temperature: Water evap.-pan θ_w (5)	w (6)	(V-v) (7)	E (8)
	feet	inches	°F	°F	mi/hr	inch	inch/day
Imperial, California	-68	29.86	81.4	78.4	1.96	0.632	0.384
Fort Calhoun, Nebraska	1160	28.77	67.1	70.1	1.35	0.301	0.174
Logan, Utah	4778	25.07	67.6	70.0	1.89	0.470	0.293
Fort Collins, Colorado	5000	25.02	55.0	58.1	1.01	0.293	0.149
Lake Tahoe, California	6300	23.76	55.1	61.8	1.02	0.366	0.222
Victor, Colorado	10089	.....	51.0	54.9	3.15	0.187	0.170
Pike's Peak, Colorado	14109	18.07	40.8	42.5	6.04	0.117	0.149

Table 14--Relation of evaporation-coefficient to elevation

B (1)	Elevation (2)	$\frac{29.9}{B}$ (3)	Carpenter (4)	Rohwer (5)	Horton[a)] (6)
inches	feet				
29.90	0	1.00	1.00	1.00	1.00
27.8	2000	1.075	1.10	1.045	1.042
25.9	4000	1.155	1.20	1.08	1.09
24.0	6000	1.245	1.29	1.12	1.142
22.3	8000	1.34	1.38	1.16	1.20
20.6	10000	1.45	1.46	1.195	1.26
19.1	12000	1.57	1.54	1.225	1.33
17.7	14000	1.69	1.60	1.255	1.40

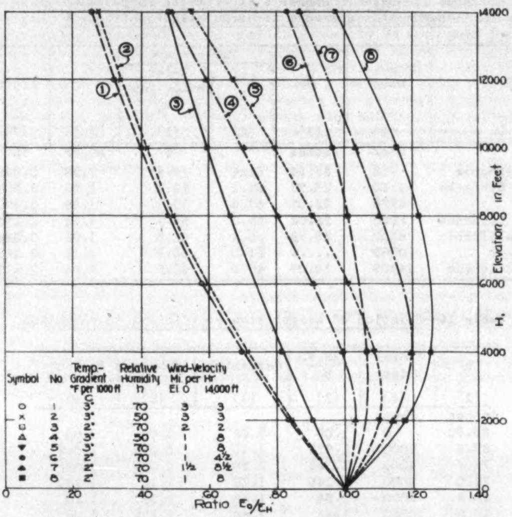
[a)] For $\theta_o = 70°F$, lapse-rate 3° per 1000 feet, w = 3 miles per hour, relative humidity = 37 per cent.

Columns 3, 4, and 5 show the relative evaporation-coefficients for different barometric pressures and elevations, computed in accordance with the inverse barometric pressure rule, Carpenter's formula, and Rohwer's formula, respectively. All are referred to an evaporation-coefficient unity at sea-level.

Column 6 shows similar figures computed by the author's formula (29) for a sea-level temperature 70°F, lapse-rate 3° per 1000 feet, w = 3 miles per hour, h = 37 per cent. This gives good agreement with Rohwer's formula and experiments up to 6000 feet elevation and gives, as does Rohwer's formula, a much smaller increase in evaporation-coefficient with increasing elevation than is obtained from the inverse barometric pressure rule. Considerable departures of the calculated values in column 6 from the observed values obtained by Rohwer are to be expected because of the variations in wind-velocity and relative humidity at the different stations shown by Table 14. It appears that the use of an inverse barometric pressure factor in an evaporation-formula of the Dalton type is not confirmed either by theory or experience and that the increase in the evaporation-coefficient with increased elevation is much less than such a factor indicates.

Calculated evaporation-profiles

Figure 8 shows a number of vertical evaporation-profiles calculated by the use of the author's formula (28), including allowance for variation in barometric pressure. Data for temperature, temperature lapse-rate, wind-velocity, and relative humidity, on which the different curves are based, are given on the diagram. It will be noticed that curves 4 to 8, inclusive, all show a maximum at some elevation above sea-level and resemble closely in form the curves shown on Figure 6, obtained from observations at Class A evaporation-stations for the summer season. Curves 1, 2, and 3 resemble



Symbol	No	Temp-Gradient °F per 1000 ft C	Relative Humidity h	Wind-Velocity Mi. per Hr El 0	Wind-Velocity Mi. per Hr 14000 ft
○	1	3°	70	3	3
×	2	3°	50	3	3
▫	3	2°	70	2	2
△	4	3°	50	1	8
▼	5	3°	70	1	8
●	6	2°	70	1	4½
▲	7	2°	70	1½	8½
■	8	2°	70	1	8

FIG. 8-VERTICAL EVAPORATION PROFILES CALCULATED FOR VARIOUS CONDITIONS

the Mount Whitney evaporation-profile, Figure 7. It is possible, with a suitable combination of temperature, humidity, and wind-velocity, for the profile to be nearly a vertical line, as observed in the Alps by Maurer and Lütschg. It is evident that a wide variety of forms of vertical evaporation-profiles may occur, the most common form having a maximum at some elevation above sea-level. The observed curves given on Figures 6 and 7 are not inconsistent.

Evaporation from and condensation on snow and ice

The preceding discussion has dealt mainly with evaporation- and water-losses below the limit of perpetual snow and below the limit of vegetation. Above or north of these limits practically the only water-loss is the evaporation from snow- and ice-surfaces, where results obtained as to water-losses and evaporation below these limits do not apply. In general it has been assumed that evaporation from snow and ice follows the same laws as evaporation from water-surfaces if the small difference in vapor-pressure over ice and water at the same temperature is taken into account. The differences in conditions are, however, so great that evaporation from snow requires separate treatment. The principal differences are:

(1) Fresh, loose snow may contain 90 per cent of air-space. The area exposed to evaporation and condensation may, therefore, be greater than the projected area and theoretically, at least, evaporation or condensation may be greater than on an equal projected area at the same temperature.

(2) The temperature of a snow- or ice-surface cannot rise appreciably above 32°, whereas the air-temperature may rise much higher. Differences between air and snow surface-temperatures are frequently many times as great as the difference between air-temperature and the temperature of a water-surface.

(3) When there is a large excess of air over evaporating surface-temperature, as in summer over a snow-surface, the vapor-pressure in the air may exceed the vapor-pressure for 32° temperature, and conditions favor condensation where they would favor evaporation over a water-surface with the same air-temperature.

In measuring evaporation from snow, the evaporation-surface can be and usually is continuous with the surrounding snow, so that the application of an area-factor, such as is required in case of the measurement of evaporation of water from pan-atmometers, in order to determine the true evaporation from a broad surface, becomes unnecessary.

It is a matter of common experience that measurable condensation on a surface of an evaporation-pan is rarely observable. This may be in part because evaporation-observations are usually taken at 24-hour intervals and the net result may be positive, or evaporation, for the 24-hour period even though condensation may have taken place during part of the period, especially at night. These conditions have been observed at the Class A United States Weather Bureau evaporation-station at the author's Laboratory, but condensation has been observed only when the air was nearly quiet.

The relatively high water-yield of many mountain glacier drainage-basins, the apparently small water-losses from drainage-basins at high elevations or in high latitudes generally, and, in particular, the small apparent water-losses from drainage-basins in middle latitudes during the season of snow-cover are results of direct observation. For mountain drainage-basins in middle latitudes where rainfall-data are reasonably extensive and accurate runoff-records are available, the apparent water-losses or difference between measured rainfall and measured runoff are not infrequently found to be negative for the winter season. To account for these facts the idea that precipitation at high elevations and in high latitudes is supplemented by direct condensation has often been invoked.

On any water-, ice-, or snow-surface, vapor-emission and vapor-return are both taking place simultaneously and continuously. If the net result for a given time-interval is a loss, it is credited as evaporation. If there is a gain, it is credited as condensation. There may be a gain part of the time and a loss part of the time, but there cannot be a net loss by evaporation and at the same time a net gain of available water-supply over precipitation by condensation.

Various efforts have been made to measure evaporation from or condensation on snow. The results in middle latitudes have usually come out positive, that is, appreciable amounts of evaporation are observed and little or no condensation.

The avoidance of serious errors in the measurement of the evaporation from snow under natural conditions is a difficult matter. Few if any of the meager published data on this subject are of certain reliability. Lee (Charles H. Lee, Water-resources of a part of Owens Valley, California, W.S.P. 294, Washington, 1912, pp. 49 and 118) gives the results of observations on evaporation from snow at elevation 5100 feet in the San Bernardino Mountains, California, latitude 34°, which show an average daily evaporation from snow of 0.1 inch during five winter months. This was, however, from 2 to 12 times the evaporation from a water-surface. The snow-prism from which the evaporation was measured projected above the lip of the rain-gage can and it is possible that a large error was introduced as a result of water derived from melting snow running down the outside of the rain-gage can. Observations by the author for a few days at Albany, New York, in January 1914 indicated evaporation from a snow-surface of 0.028 inch per day or about one-inch depth per month, with maximum air-temperatures ranging from 19° to 39° and wind-velocities of 7.5 to 12.6 miles per hour (Robert E. Horton, Evaporation from snow, Mon. Weath. Rev., Feb. 1914, pp. 99-100).

The figures last given are not inconsistent with the results indicated by the studies of the apparent water-losses from snow-covered drainage-basins in eastern mountain regions, which frequently range from 1 to 1 1/2 inches per month.

Rolf's experiments--The experiments of Rolf relative to condensation on and evaporation from snow are of particular interest as they cover observations for the period December 1905 to July 1906, inclusive, at Vassijaure, "a little lake in Swedish Lapland," apparently somewhat north of the Arctic circle (Note sur la condensation et l'évaporation qui se produisent à la surface d'une couche de neige (Fr.), Arkiv för

Matematik, Astronomi, och Fysik, Band 9, No. 35 (1914), K. Svenska Vetenskapsakademien i Stockholm). The observations were made with zinc pans about 24.85 cm square and 3.33 cm deep, painted with white lacquer. The pans were filled with snow to their rims, then embedded in the snow until the rim of the pan was flush with the surrounding surface. The pans were exposed in the winter, spring, and summer, until the snow disappeared late in July. The pans were exposed for 24 hours in winter, for 12 hours at night in summer, and for periods of 2 to 4 hours in the daytime in summer. In the summertime the pans were exposed at different hours of the day from morning till evening. Many experiments were rejected because of drifting of snow into the pans, especially in winter, precipitation during the experiment, and, as Rolf states, because "the differences in weight of the sample weighings, without apparent reason, required that certain samples be rejected." Results were also rejected for pans exposed in the summertime when melting occurred if more than one-fifth of the surface of the pan was covered with liquid water. For the remainder of the experiments Rolf gives the evaporation or condensation-depth in millimeters, which have been reduced to 24-hour rates. He also gives the air-temperature, vapor-pressure in the air, and wind-velocity. The point where wind-velocity was taken, relative to the position of the pans, is not stated. The wind-velocities are relatively high, generally ranging in summer from three to eight meters per second. In winter the wind-velocities were low and uniform, ranging from one to two meters per second. Owing to the fact that the snow was melted elsewhere, beginning June 30, 1906, "the pans were set in a snow-bank in a little ravine facing the east." Here apparently the wind-action was greatly reduced.

Rolf concludes: (1) That there was no apparent correlation between the evaporation or condensation and wind-velocity and other factors; (2) that the net condensation for the months of June and July, 1906, was 4.6 and 36.2 mm, respectively; and (3) that at Vassijaure "condensation is not an important factor, amounting, in the case of a snow-surface, to only a few millimeters per month."

In order to test the validity of these conclusions an analysis of Rolf's data, where temperature and wind-velocities are given, was made along the following lines.

Using Rolf's data of snow-surface temperature for winter conditions when the air-temperature was below 0° C, and assuming snow-surface temperature as 0° C when the air-temperature was above 0° C, the value of the Dalton difference-term $(V - v)$ was computed for evaporation in still air. $C\,(V - v)$ was also computed, using the value $C = 0.40$ in. per 24 hours, as determined by Fitzgerald and the author for middle latitudes. The ratio of the evaporation or condensation without wind-effect, to the calculated evaporation or condensation in still air, was then determined, with the following results.

For winter conditions, with air-temperature below 0° C, the average ratio is 0.99 in eight experiments showing condensation, and 1.03 in one experiment showing evaporation. In other words, Rolf's experiments are in nearly perfect agreement with the Dalton formula and the author's evaporation-formula, for winter conditions, assuming that the wind-velocity at the snow-surface was negligible.

For summer conditions and daytime observations the average apparent condensation is close to six times the amount which should take place in accordance with the Dalton formula, while in cases where evaporation occurred during the same period the average ratio is about 1.2. The last result is about what would be expected for evaporation subject to moderate wind-action. While in the majority of cases the ratio of condensation to that indicated by the Dalton formula is from two to four, yet there are many instances where much higher ratios occur, ratios of 7, 11, 34.5, 50, and 66.5, for example. The occurrence of these high ratios for condensation and the fact that the results are in good agreement with the calculated results for evaporation-conditions and for condensation in winter indicates strongly that there is some large element of error in the observational data for summer conditions when melting took place.

Taking the observations as they stand and averaging the results algebraically, that is, subtracting the total measured evaporation from the total measured condensation, the net result is an average condensation during the summer months while snow remains on the ground of 0.611 mm per day or 1.83 cm per month. This result is not, in itself, unreasonable, and if true would indicate an appreciable increase in available moisture-supply by condensation in extreme northern regions of low precipitation.

An analysis was also made to determine whether the experiments showed any definite relation of rates of evaporation and condensation to wind-velocity. For this purpose group-means were taken of observations under summer conditions with wind-velocities less than 2 m/sec, 2 to 3 m/sec, and so on. The ratio of the observed condensation or evaporation to that indicated by the Dalton formula for still air was set down opposite the wind-velocity in each instance. The results are given in Table 15 in cases where condensation occurred.

Table 15--Relation of wind-velocity to condensation, Rolf's observations

Number of observations (1)	Average wind-velocity (2)	Average ratio (3)
	m/sec	
3	0.67	1.25
14	2.5	8.33
10	3.48	8.58
10	4.33	2.00
10	5.33	3.53
2	6.45	-0.65

A similar tabulation was made of the less numerous data when evaporation occurred, with the results given in Table 16. Considering the paucity of data the apparent increase of evaporation with increased wind-velocity is in good agreement with experience elsewhere. Certainly it is difficult to accept the conclusion that condensation takes place at six times the rate indicated by the Dalton formula for still air under conditions where, when evaporation occurs at practically the same wind-velocities, the rate is only 1.2 times that indicated by the Dalton formula for still air.

Table 16--Relation of wind-velocity to evaporation, Rolf's observations

Number of observations (1)	Average wind-velocity (2)	Average ratio (3)
	m/sec	
3	3.3	0.664
3	4.6	1.11
2	5.4	1.20
3	7.2	1.26

The results of Rolf's observations on condensation in summer, as shown in Table 15, if valid, indicate that the condensation-rate decreases as the wind-velocity increases.

The effect of wind-action on condensation is subsequently discussed. It appears inadequate to account for the apparent high rates of condensation observed by Rolf, as shown by Table 15, as compared with the calculated rates for still air. The author believes that Rolf's results for still air and winter conditions are substantially correct but that his data for condensation under summer conditions when melting occurred are invalid and must be rejected. Rolf states that the rim of the evaporimeter was depressed below the surface of the surrounding snow. It seems probable that under these conditions water derived from the melting of the surrounding snow flowed into the evaporation-pan or was blown into the pan as fine spray by the high winds.

Rohwer's experiments on evaporation from ice

Observations of evaporation from ice in perfectly still air under well-controlled laboratory conditions were made by Rohwer (op. cit.) at Fort Collins, Colorado, in the winter of 1928-29, using a pan 17 inches in diameter, filled with ice. Observations are reported for 32 days during which the conditions were relatively uniform. The average results are as follows: Air-temperature, 27.°6 F; ice surface-temperature, 27.°0 F; (V - v), 0.026 inch of mercury; observed evaporation, 0.0079 inch per 24 hours; and calculated evaporation, 0.0114 inch per 24 hours.

The calculated evaporation was obtained by the formula derived by Rohwer for still air

$$E = 0.44\,(V - v)$$

That the low observed evaporation-rate was due to a stagnant air-layer adjacent to the ice-surface is indicated by a second series of experiments with the same apparatus, with an electric fan running in the room but so placed as not to rotate a Robinson anemometer near the pan. The average results of observations for 12 days are as follows: Air-temperature, 25.°8 F; ice surface-temperature, 24.°4 F; (V - v), 0.029 inch of mercury; observed evaporation, 0.0119 inch per 24 hours; and calculated evaporation, 0.0127 inch per 24 hours. It will be noted that in perfectly still air the observed evaporation from ice was about 8/11 of the computed amount, while with an inappreciable air-movement the evaporation from ice became almost equal to the computed amount.

Rohwer also carried out experiments on evaporation from ice with various wind-velocities, but in the dry climate of Fort Collins conditions favoring condensation did not occur during the period of his experiments. The results can only be used inferentially in determining the effect of wind-velocity on condensation.

Relation of wind-velocity to condensation

Condensation can occur only when the Dalton difference-term (V - v) is negative, that is, when the vapor-pressure v in the air is greater than the vapor-pressure corresponding to the temperature of the evaporating surface.

In ordinary evaporation-formulas such as (23) the wind-factor is applied directly to (V - v),and if this is correct, an increase in wind-velocity should increase condensation in the same way and to the same extent that it increases evaporation. In accordance with the author's formula the wind-factor applies only to V and wind-action increases the rate of removal of newly emitted vapor whether the conditions are such as to favor evaporation or condensation, that is, whether (V - v) is positive or negative. In accordance with this formula wind tends to decrease condensation in the same way that it tends to increase evaporation, and evaporation may occur in the presence of wind under conditions such that condensation would occur in still air, that is, when (V - v) is negative.

In accordance with the author's formula, when the vapor-pressure in the air is greater than V, the presence of wind has no effect on the rate of vapor removal or return by diffusion; hence it does not affect the term (V - v). That this is true except in the case of nearly stagnant air is indicated by the following consideration. If there is wind and the air is warmer than the evaporating surface, there is a tendency toward the formation of a layer of cold stagnant air over the evaporating surface. If the vapor-pressure in the air exceeds V there is a tendency to exhaustion of the vapor by downward diffusion from this stagnant air-layer. Under these conditions condensation would occur but at a gradually decreasing rate. If, however, there is even a slight wind, the stagnant air-layer may be broken up and fresh air, with its full quota of vapor, is brought in contact with the evaporating surface. Vapor return will then take place continually at a rate proportional to v. A current of air can, however, do no more than to maintain the vapor-pressure over the evaporating surface continually equal to v. A high wind-velocity has no greater effect in this respect than a slight wind. Conditions such as described are clearly indicated by Rohwer's experiments above given, which indicated a rate of condensation in perfectly still air less than that corresponding to the calculated rate but equal to the calculated rate in an extremely slight wind. If, then, (V - v) is negative and the conditions favor condensation, it is evident that wind--except a slight wind--does not affect the rate of vapor-emission and return by diffusion but it does increase the rate of mechanical removal of newly emitted vapor. Consequently it appears that wind tends to decrease condensation instead of increasing it. This result is indicated by Rolf's experiments, above cited.

Effect of snow-air temperature-difference

The effect on evaporation or condensation of differences between air-temperature and the temperature of the evaporating surface is one of the unsolved problems of evaporation. The temperature of a snow-surface cannot rise appreciably above 32°. On bright, warm days the temperature of the air may rise 20° or 30°, or even more, higher than the temperature of the snow-surface. The difference between air and snow-surface temperatures is often ten to twenty times as great as the difference commonly occurring between air-temperature and the temperature of a water-surface. If, therefore, difference between air and evaporating surface-temperature has any important effect on evaporation, this effect must be much greater in case of evaporation from or condensation on snow than in case of evaporation from a water-surface.

The rate of diffusion of vapor in air varies as some power--probably between the three-halves and the square--of the absolute temperature of the air. For a given water surface-temperature, vapor removal by diffusion should, therefore, increase with excess of air over water surface-temperature. Parshall (Ralph Parshall, Trans. Amer. Soc. C.E., v. 90, June 1927, p. 318) found that in still air the evaporation-rate was a maximum when the air-temperature was the same as that of the water-surface. This is apparently explained by the fact that if the air is warmer than the water, convection is inhibited, while if the air is colder than the water and quiescent, convection may not occur unless the temperature-difference exceeds a minimum value. At the same time the rate of vapor removal by diffusion is decreased as compared with that for a temperature equal to the water-temperature.

Some of the existing evaporation-formulas include absolute air-temperature as a factor. While the investigation has not been completed, neither the application of a factor for absolute air-temperature nor for difference between air and water surface-temperatures to the evaporation data by Rohwer seems to show any material improvement in the relation between calculated and observed evaporation as compared with that obtained without including such a factor.

In case of a snow-surface where there is a large temperature-difference between the air and snow and conditions favor condensation, wind tends to break up the layer of stagnant air over the snow-surface, replacing it with much warmer air and hence tends to increase the rate of diffusion both from and to the snow-surface. Since the latter in this case is the greater, it seems certain that the large excess of air over snow surface-temperature frequently occurring must tend to increase the rates of evaporation and condensation. Like barometric pressure, the air-water temperature-difference apparently only affects vapor removal or return by diffusion, which may be relatively small compared with vapor removal by wind-action.

Over a broad snow-field the actual vapor-pressure v is determined largely by the rate of evaporation from the snow-surface and hence is not likely to exceed V. In case of a mountain glacier the conditions are different. If there is a wind blowing across the glacier-surface it may be charged with vapor derived from adjacent regions devoid of snow and ice, where the temperature of the evaporating surface is nearly the same as that of the air and where transpiration by vegetation may be added to direct evaporation. Under these conditions the vapor-pressure v in the air may easily rise above V, corresponding to the ice surface-temperature. It is to be expected that relatively much larger amounts of condensation may occur on mountain glaciers than can occur on continuous snow- or ice-fields in polar regions.

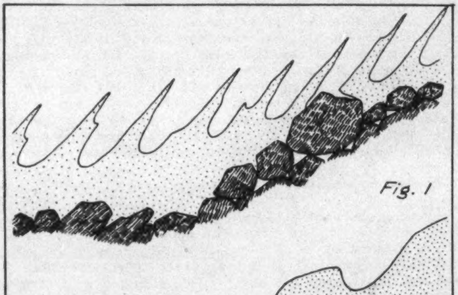
Voorheesville, New York

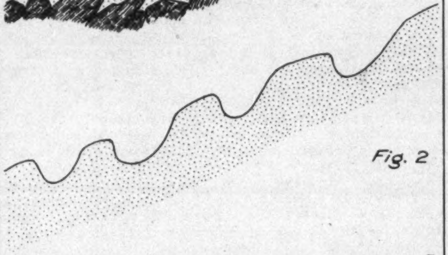
ABLATION OF SNOW-FIELDS AT HIGH ALTITUDES BY RADIANT SOLAR HEAT

François E. Matthes

Snow-fields and the so-called névés of glaciers on lofty mountains often present a peculiar, honeycombed appearance, the surface being pitted with deep cell-like hollows a foot or two feet in diameter and from a few inches to several feet in depth. When typically developed these hollows are closely spaced, the divides between them consisting merely of attenuated blades and pinnacles of hard, granular snow (Fig. 1). The hollows are alined roughly in rows and sunk at a uniform, high angle, all in the same direction.

The pinnacles have come to be known in the literature by the picturesque name of "nieve penitente"--a contraction from "nieve de los penitentes", which is the popular





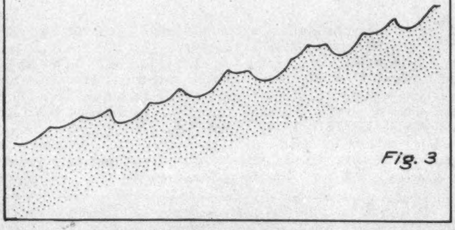


Fig. 1--Sectional view of maturely developed sunpits about 2 feet in depth (drawn from a photograph taken in the Sierra Nevada at an altitude of 13,000 feet)

Fig. 2--Sectional view of sunpits in an early stage of development; intermediate portions of snow-field still unconsumed

Fig. 3--Typical suncups such as occur in the Sierra Nevada at altitudes above 10,000 feet; these are mature forms due to long-continued ablation, yet the hollows are only a few inches deep name for them in the Andes of Argentina and means snow resembling penitent monks. The Germans have translated this to "Büsserschnee", but they also employ the term "Zackenfirn." None of these foreign terms has found, nor is likely to find, general acceptance in this country, all of them being for English-speaking people awkward to pronounce. Besides, they are unwieldy and ill adapted for technical use. It seems in order, therefore, to seek an appropriate and convenient English term.

In this quest for a new term, however, it is to be borne in mind that the blades and pinnacles, though conspicuous to the eye, are merely secondary, residual features. The hollows are genetically the primary and significant forms. They develop each as an independent unit, often at distances of several feet from one another (Fig. 2), and it is for them that a new term is most urgently needed. In a previous paper the author tentatively suggested the terms "suncups" and "honeycombs" (F. E. Matthes, Mount Rainier and its glaciers, Dep. Interior, Washington, D. C., pp. 17-18, 1914). Here he proposes more formally the term "suncups" for the shallow hollows, only a few inches in depth (Figs. 2 and 3), that occur in great abundance on the lower snowfields of high mountains and occasionally at moderate elevations, as low even as sealevel. The term not only is in a measure expressive of the smoothly concave form of these hollows but links them with the source of energy by which they are called forth. In addition it has the advantage of forming a convenient adjective, so that a snowfield may be graphically described as "suncupped" throughout.

For the much less common cell-like hollows several feet in depth that develop from suncups only at very high altitudes, and there only under special weather-conditions, the term "sunpits" is here proposed. ("Honeycombs", though suggestive of the cell-like forms of the hollows and of their arrangement in rows, seems less appropriate nevertheless.) "Sunpits" also links the hollows in question with the rays of the Sun, but indicates greater depth than suncups. The similarity of the two terms, moreover, indicates the close genetic kinship of the two types of forms. "Sunpits", finally, also lends itself to use in adjectival form.

Adoption of these new terms, it is to be noted, will not eliminate "nieve penitente", "Büsserschnee", or "Zackenfirn" from possible use. These terms remain available, for any one who may wish to employ them, to designate the snow-pinnacles between the sunpits. Helpful criticism and suggestions are invited in regard to these matters of nomenclature, for it seems desirable that the students of snow and of glaciers, in this country at least, reach an agreement on the terminology of this part of their science. Meanwhile the terms "suncups" and "sunpits" will be used in this paper.

Suncups and sunpits are strictly evaporation-hollows. They are generally conceded to be such, and the radiant heat of the Sun is recognized as the agent that produces them. No attempt will here be made to review the extensive literature on the subject, which begins with Darwin, nor to trace the steps whereby the present understanding of their nature and mode of origin has been achieved. It will suffice to enumerate the salient facts concerning the mode of occurrence of sunpits and suncups, and to state the essence of the generally accepted theory as to the process of their evolution.

The facts are:

(1) Typical sunpits occur only at very high altitudes. In the Andes their lower limit appears to be about 12,000 feet; on the Kilimandjaro group in equatorial Africa it is about 15,000 feet; in the Himalayas probably about 16,000 feet. No upper limit to their range has yet been reported. On Chimborazo they have been observed at 18,000 feet and on Mount Nieves Penitentes, in the Nun Kun Range of the Himalayas, at above 19,000 feet.

(2) From his own observations the author may add that splendidly developed sunpits occur in the Sierra Nevada at altitudes from 12,000 feet upward and on Mount Rainier occasionally as low as 11,000 feet but, as a rule, above 12,000 feet.

(3) Suncups a few inches in depth occur in the Sierra Nevada at altitudes as low as 10,000 feet and on the lower slopes of Mount Rainier down to about 8000 feet.

(4) Typical sunpits develop only on mountains in low and moderate latitudes. They have not been observed (as far as known) in the Rockies and Selkirks of Canada, nor on

the mountains of Alaska. They are absent in the polar regions. On the other hand, they attain greatest depth near the equator. In the Andes depths of 15 to 18 feet have been measured.

(5) Typical sunpits develop only on mountains that have a dry summer climate and that are exposed to strong insolation for prolonged periods. They are unknown in the European Alps, which have a prevailingly humid climate, but shallow suncups are produced there occasionally.

[The frequent occurrence of well-developed sunpits on Mount Rainier is of peculiar interest in view of the high latitude of that peak--46° 50'--and also in view of its reputedly humid climate. The fact is, however, that the summit of Mount Rainier rises well above the zone of maximum cloudiness and precipitation, and often has from five to ten consecutive days of sunshine in summer.]

(6) The angle at which the blades and pinnacles of snow between the sunpits lean corresponds to the elevation of the Sun at midday. In the Northern Hemisphere they lean toward the south; in the Southern Hemisphere they lean toward the north. At the equator they stand vertical.

(7) Sunpits and suncups attain typical forms only in clean snow. Rock fragments and wind-blown dust interfere with their orderly development and tend to produce irregular forms. Sunpits and suncups are not to be confused with "dust-wells" or cryoconite basins and cavities.

(8) Sunpits and suncups are produced without visible liberation of melt-water and are at all times dry. Melt-water, if it accumulates at the bottom of a hollow, retards and may frustrate entirely its further development by refreezing into a cake of hard ice.

Theory of development--It is generally agreed that sunpits and suncups are produced by the radiant heat of the Sun. It transforms the snow directly into water-vapor, which is absorbed by the dry air as fast as formed. A part of the water-vapor, nevertheless, is sublimated on the sides of the hollows, and as a consequence these are converted by progressive recrystallization into firn, granular névé.

The inception of suncups and sunpits is traceable to the original unevennesses of the snow-field. The inevitable effect of the Sun's rays is to accentuate the depth of any initial concavity, however slight and by whatever cause produced. That part of the concave surface upon which they impinge at right-angles at midday--when they are strongest--will waste away more rapidly than any other part, the amount of solar heat received per unit of surface varying as the cosine of the angle of incidence (Figs. 4 and 5). Moreover, there will be a concentration of solar heat at the bottom of each pit as a result of reflection from the sides. Thus each pit will be deepened more rapidly than widened, and always in the direction of the Sun's rays at midday.

The deeper the pit grows, the more nearly parallel to the direction of strongest insolation its north and south walls will become, and the less ablation these will suffer. The west wall, meanwhile, suffers mild but increasingly intense ablation during the morning hours, and the east wall suffers diminishing ablation during the afternoon hours, and so the hollow tends to become elongate in east-west direction. If the period of dry, sunny weather lasts long enough the west and east walls will be partly destroyed, and adjacent pits will finally coalesce, so as to form an east-west trench or furrow with uneven bottom.

The intimate details of the process need not be pursued further here, for they are of little consequence to either the meteorologist or the hydrologist. But one point deserves more emphasis than it has been given hitherto, namely, that low air-temperatures, at or below the freezing-point, are indispensable for the typical development of sunpits. In other words, it is essential for best results that atmospheric heat shall have no part in the ablation of the snow-mass.

The rays of the Sun, it is to be borne in mind, impinge at midday normally upon the bottoms of the pits and likewise upon the crests of the partitions (Fig. 5). They act with equal intensity on both. What is more, they shine all day long, from one

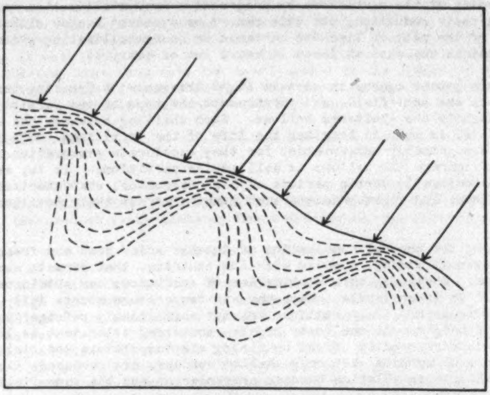


Fig. 4--Sectional view showing development of deep sunpits from shallow concavities in surface of snow-field; arrows indicate direction of Sun's rays at noon; curves are drawn empirically only

direction or another, upon the upper parts of the partitions, but only for a few hours in the middle of the day upon the bottoms of the pits. Again, the partitions are inherently much more vulnerable to insolation than the bottoms of the pits, because they have a much greater area of exposed surface per unit of volume than the latter. Especially is this so when they are reduced to attenuated blades and pinnacles such as are shown in Figure 1. Yet the pits are lowered more rapidly from day to day than the partitions. There must then be some additional agency or agencies that operate either to accelerate ablation in the pits or to retard it on the partitions, or to do both.

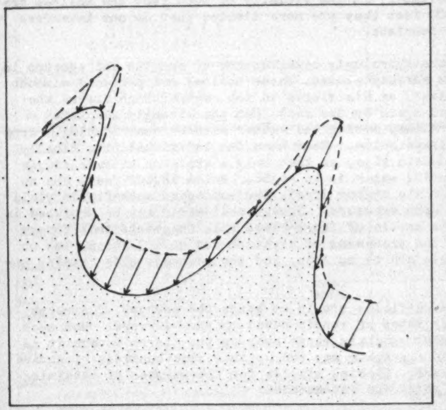


Fig. 5--Idealized sectional view of a sunpit and adjoining partitions; arrows indicate direction of Sun's rays at noon, their plotted lengths indicating the relative intensity of insolation at each point, which is proportional to the cosine of the angle of incidence (Note that the maxima at the bottom of the pit and on the tops of the partitions are equal)

The concentration of solar heat at the bottom of each pit by reflection from the walls doubtless is a factor, but the excess of heat thus created cannot be considerable in view of the great capacity that snow has for absorbing radiant solar heat (N. N. Kalitin, Radiant properties of a snow-cover, Bull. Observ. Géophys. Central, Leningrad, Nos. 1-2, pp. 9-18, 1931). It is not likely, therefore, that this slight concentration of solar heat would alone account for the rapid deepening of the pits.

The hardening of the partitions by progressive recrystallization doubtless operates to retard their reduction, but this cannot be a potent factor either, for the snow at the bottom of the pits is likewise hardened by recrystallization whenever it is in shadow--and that is the case at least 18 hours out of every 24.

A much more potent agency is seen in light breezes with freezing temperatures that waft across the snow-fields and refrigerate the tops of the partitions while affecting but slightly the sheltered hollows. Such chilling breezes, the author is inclined to believe, do much to lengthen the life of the partitions. Strong gales, on the contrary, are probably unfavorable, for they accelerate evaporation from the partitions and refrigerate the hollows as well as the partitions. It is, as a matter of observation, preeminently during periods of high barometer, characterized by cold, clear, dry weather, and light breezes, that sunpits attain their most perfect development.

It is, then, the unusual combination of intense solar heat and freezing air-temperatures, even at midday, coupled with low humidity, that permits sunpits to attain great depth. Obviously this combination of conditions can obtain only at very high altitudes. At lower levels, where the air-temperature mounts daily appreciably above the freezing-point, the partitions are not sufficiently refrigerated to maintain any considerable height. At the lower levels, moreover, solar heat is less intense, and its effect is more readily offset by rising air-temperature and rising humidity. For these reasons no sunpits, but only shallow suncups, are produced. And at still lower levels atmospheric ablation becomes preponderant and the snow-fields melt down evenly.

On a peak such as Mount Rainier, whose snowy robe in early summer has an altitude range of fully 10,000 feet (from 14,400 to about 4000 feet) the gradation from deep sunpits at the top to shallowest dimples below is often impressively displayed. Above 13,000 feet the pits may be two feet deep, offering an exasperating impediment to the mountaineer; at 12,000 feet they are likely to be only one foot deep; at 10,000 feet they degenerate into suncups half a foot in depth and so broadly open as to be an aid rather than an impediment to the climber; in the vicinity of 9000 feet the hollows are only a few inches deep, and at 8000 feet they are mere dimples that do not interfere with the pleasurable glissades of tourists.

In conclusion, a word about the hydrologic significance of sunpits and suncups in snow-fields on high mountains. As already stated, these hollows are produced without the liberation of melt-water. Indeed, on his visits to the central High Sierra the author has been impressed again and again by the fact that the strongly sunpitted snow-fields above 12,000 feet waste away during the summer without contributing a drop of water to the streams in the valleys below. Even when the individual pits finally reach down to the rocks of the mountain side, so that only a skeleton of snow-ridges and snow-pinnacles remains, no running water is in sight. Below 12,000 feet, and as far down as about 11,000 feet (near the timber line), the suncupped snow-fields yield a little running water, depending upon exposure. Enough melt-water may be produced in the middle of the day to drench the mantle of frost-riven rock fragments that covers the mountain side, and to promote the processes of nivation and solifluction, but no rivulets capable of eroding channels are to be seen, and the mountain-side remains unfurrowed by ravines.

It follows that these upper snow-fields are in no sense the sources of streams and are to be excluded from any estimates of runoff based on snow-surveys. How much of an area may be involved in a great mountain range such as the Sierra Nevada it is as yet impossible to estimate. The aggregate may run up into some hundreds of square miles, or it may be considerably less. Special studies for the purpose of obtaining more accurate information on this point are recommended.

It follows, further, that the lofty névé fields at the heads of glaciers--as, for instance, those on the broad summit of Mount Rainier--contribute nothing, from their surfaces at least, to the runoff from the glaciers. From their basal layers small quantities of water may possibly be released by the warmth of the mountain and by pressure melting, but for practical purposes these quantities are probably negligible. It is from the lower portions of the glaciers that the great floods of melt-water in summer are derived. On the glaciers of Mount Rainier surficial melting in sufficient quantities to produce rills and rivulets on the ice does not extend above an altitude of about 7500 feet. On warm days these streamlets form miniature river-systems, with miniature waterfalls, lakes, and canyons cut in the ice. They are truly impressive for the volume of water they carry off, but far more impressive, if one stops to consider it, is the fact that from this low level upward to the summit of the peak--through an altitude range of some 7000 feet--the snow and névé extend with dimpled, suncupped, sunpitted surfaces that are perpetually dry.

U. S. Geological Survey,
Washington, D. C.

THE MEASUREMENT OF PRECIPITATION ON A WINDY MOUNTAIN SUMMIT
(Results of experiments on Mount Washington, New Hampshire)

Salvatore Pagliuca

On Mount Washington the problem of precipitation-measurement is complicated by the extremely high wind-movement, and by topographic peculiarities of the summit. With a minimum monthly average movement of 25 mi/hr (11.2 m/sec) and a maximum of 59 mi/hr (26.4 m/sec) as recorded in 1933, with extremes frequently above 100 mi/hr (44.7 m/sec), reaching at times 150 to over 200 mi/hr (67 to 100 m/sec), the problem is chiefly reduced to the elimination of the direct disturbing effects of the wind at the rim of the gage, and the influence of topography on the distribution of precipitation on various sectors. The conical shape of the summit with slopes of various inclination and the presence of several buildings and other obstructions made necessary the placing of several gages at cardinal points with respect to the summit.

As a result of numerous measurements made on Mount Washington in the past nineteen months, it was found that in a calm the various gages will collect nearly the same amount of precipitation. With wind-velocities between 0 and 30 mi/hr (13 m/sec)

Table 1

SNOWFALL
4 UNSHIELDED GAGES

WIND		% OF AV. CATCH OF ALL GAGES		DIFF. += EXCESS OF LEEWARD	MAX	MIN	MIN %	REF. GAGE	REMARKS
AV. DIR.	AV. VEL. MPH	LEEWARD	WINDWARD		GAGE #	GAGE #	OF MAX	% OF AV.	
W	0-29	154	46	+108	2	6	24	52	
	30-75	131	69	+62	2	5	46	62	
	OVER 75	103	97	+6	2	5	60	77	
	ALL VELOCITIES	131	69	+62	2	5		64	
E	30-75	137	63	+74	5	6	48	236	
S	30-75	145	55	+90	6	5	24	41	
	OVER 75	124	76	+48	6	5	18	36	
NW	0-29	111	89	+20	5	6	35	133	
	30-75	126	74	+52	2	6	47	82	
	OVER 75	138	62	+76	2	6	54	49	
	ALL VELOCITIES	123	77	+46					
SE	0-29	122	78	+54	6	2	36	89	
	30-75	115	85	+30	6	2	39	106	4 shielded gages
SW	30-75	120	80	+40	6	3	53	22	
NE	0-29	108	92	+16	3	2	63	106	
	30-75	123	77	+46	5	6	30	189	
	over 75	155	45	+110	6	2	7	104	
	ALL VELOCITIES	140	60	+80					

REFERENCE GAGE #5 COLLECTED 90% OF AVERAGE SNOW CATCH

SNOWFALL
4 SHIELDED GAGES

WIND		% OF AV. CATCH OF ALL GAGES		DIFF. += EXCESS OF LEEWARD	MAX	MIN	MIN %	REF. GAGE	REMARKS
AV. DIR.	AV. VEL. MPH	LEEWARD	WINDWARD		GAGE #	GAGE #	OF MAX	% OF AV.	
W	0-29	138	62	76	2	4	35	56	
	30-75	113	87	26	3	4	51	62	
	OVER 75	141	59	82	3	4	28	40	
S	30-75	131	69	62	2	4	45	36	
SE	30-75	115	85	30	6	2	39	106	
NW	0-29	81	119	38	2	4	50	60	
	30-75	54	126	72	2	4	39	65	
SW	30-75	109	91	18	2	4	45	65	

RAINFALL
4 UNSHIELDED GAGES

WIND		% OF AV. CATCH OF ALL GAGES		DIFF. += EXCESS OF LEEWARD	MAX	MIN	MIN %	REF. GAGE	REMARKS
AV. DIR.	AV. VEL. MPH	LEEWARD	WINDWARD		GAGE #	GAGE #	OF MAX	% OF AV.	
W	0-29	93	107	-14	2	3	66	104	
	30-75	113	87	+26	2	5	71	84	
E	30-75	181	19	+162	5	3	6	192	
NW	30-75	88	112	-24	5	2	63	120	
N	0-29	112	88	+24	5	2	25	176	
SE	over 75	137	63	+74	6	3	33	53	4 shielded gages
NE	30-75	171	29	+142	6	2	6	25	

REFERENCE GAGE #5 CAUGHT 108% OF AVERAGE RAIN CATCH.

COEFFICIENT OF EFFECTIVENESS FOR SHIELDED GAGES

SNOWFALL (MELTED)

AV. WIND VEL.	0-29	30-75	OVER 75
COEFFICIENT	1.34	1.69	3.00

RAINFALL

AV. WIND VEL.	0-29	30-75	OVER 75
COEFFICIENT	1.04	1.40	1.42

AVERAGE COEFFICIENT 1.53

AVERAGE EXCESS CATCH OF LEEWARD GAGES

AV. WIND VEL.	0-29	30-75	OVER 75
% EXCESS	22	86	157

MOUNT WASHINGTON, N.H.
(6284')

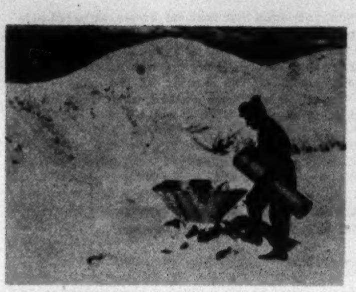


Fig. 1

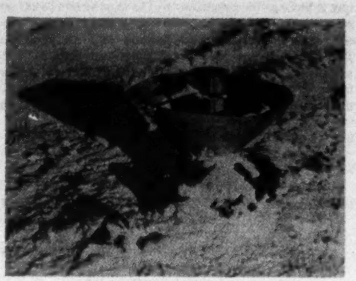


Fig. 2

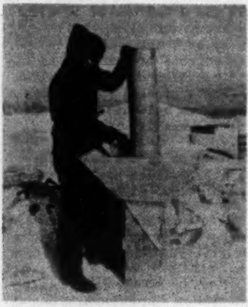


Fig. 3

Fig. 1--Shield is secured to wooden box (under the stones and snow) by strap iron; to assure continuity of collection, gages are replaced with empty ones

Fig. 2--Lower end of shield is open to allow discharge of snow (after Billwiller) but some ice gets into box below gage and raises gage above shield, where the effectiveness of shield is, consequently, reduced--note rime on gage (See text for complete description)

Fig. 3--Wooden shields (much like Röstad's) have proved to be strong and efficient, and are of simple and economical construction

the receivers placed on the lee-side slopes would collect on the average 22 per cent more than those on the windward slopes. With wind-velocities between 30 and 75 mi/hr (14 and 33.5 m/sec) the precipitation caught on the lee-side is 86 per cent in excess of the precipitation collected on the windward slopes. With wind-velocities higher than 75 mi/hr (33.5 m/sec) the excess collection on the lee-side slopes was 157 per cent (for details, see Table 1).

It is possible that the effect of drifting snow, generally proportional to the wind-force, for a given snow-cover, is more pronounced on the lee-side than on the windward, but so far as possible this effect is accounted for in snow-water measurements on Mount Washington.

Figures for rain are not as complete as those for snow-water, due to the relatively short duration of the rain-period.

With light west and northwest winds, these figures, however, seem to indicate a slight excess on the windward side. With strong west, north, and southeast winds, an excess on the lee-side is indicated. Strong east and northeast winds seem to create an excessive preponderance of rainfall on the lee-side.

These apparently discrepant results may be due in part to poor exposure of some of the gages with respect to certain wind-directions. Further tests will be conducted this summer with a larger number of gages.

A reference-gage placed to the south of the summit, approximately where the United States Signal Service standard gage was located, caught on the average 108 per

Table 2--Duration of precipitation and fog, Mount Washington Observatory, year 1933

Number of	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
Total precipitation (includes all precipitation)													
Days	19	23	21	21	22	15	20	16	15	21	24	23	240
Hours	223	202	247	231	141	57	84	66	66	129	255	197	1898
Rain (includes rain, drizzle, thunder-showers, and rain-snow)													
Days	..	..	..	9	14	11	20	16	14	12	2	2	100
Hours	...	...	...	93	100	39	83	66	60	62	10	6	519
Snow (includes granular and ordinary snow, sleet, and graupel)													
Days	19	23	21	14	9	5	..	..	4	11	24	23	153
Hours	223	202	247	138	30	17	...	...	6	65	245	194	1367
Granular snow													
Days	..	..	..	4	2	2	..	..	..	..	..	2	10
Hours	...	...	...	32	7	5	...	...	...	...	...	5	49
Sleet													
Days	..	..	1	..	..	..	..	..	1	1	1	2	6
Hours	...	...	14	...	...	...	...	...	2	1	5	2	24
Graupel													
Days	..	1	..	..	2	4	..	..	..	..	..	2	9
Hours	...	2	...	...	1	5	...	...	...	...	...	2	10
Glaze (includes ice coating from rain, drizzle, sleet, and wet fog)													
Days	..	..	..	..	3	..	..	..	..	2	1	2	8
Hours	...	...	...	...	24	...	...	...	...	5	6	7	42
Hail													
Days	..	..	..	..	3	1	1	..	..	..	..	..	5
Hours	...	...	...	...	10	1	1	...	...	...	...	...	12
Drizzle													
Days	..	..	..	3	6	2	5	2	..	1	..	2	21
Hours	...	...	...	24	30	9	15	11	...	4	...	4	97
Thunder-shower													
Days	..	..	..	..	1	5	9	3	..	..	..	..	18
Hours	...	...	...	...	1	10	7	5	...	...	...	...	23
Rime													
Days	24	27	29	16	5	..	..	..	4	13	25	29	172
Hours	366	427	480	252	48	...	...	...	27	150	387	417	2554
Rough frost													
Days	3	2	2	11	6	3	..	..	4	8	8	6	53
Hours	16	19	18	73	36	26	...	...	14	42	47	38	329
Fog (includes all kinds of fog)													
Days	24	27	29	25	23	26	28	30	24	27	26	29	318
Hours	383	446	498	431	300	308	313	316	344	371	434	456	4600

cent of the average collection of snowfall in the four gages at cardinal points, and 90 per cent of the rainfall caught by these gages.

Most important is the problem of shielding gages. Various ingenious methods have been suggested, each with its merits and its faults (see annotated bibliography of Appendix A at end of this paper, references to which are indicated by brackets).

After considerable experimenting on Mount Washington it was found that a Nipher screen [1] consisting of a sheet-iron, funnel-shaped shield with the upper diameter 35 inches (89 cm) and an angle of deviation of 45°, the gage flush with the upper level of the shield, was a practical and satisfactory design (Figs. 1 and 2). The shield is secured to a wooden box by means of strap iron. The lower part of the shield is open, after Billwiller's modification [5], to simplify cleaning snow. The height of the rim of the gage from the ground is 36 inches. Wooden shields built like a truncated pyramid, with 30-inch (76-cm) upper sides (Fig. 3), have also proved to be efficient, and of economical and simple construction.

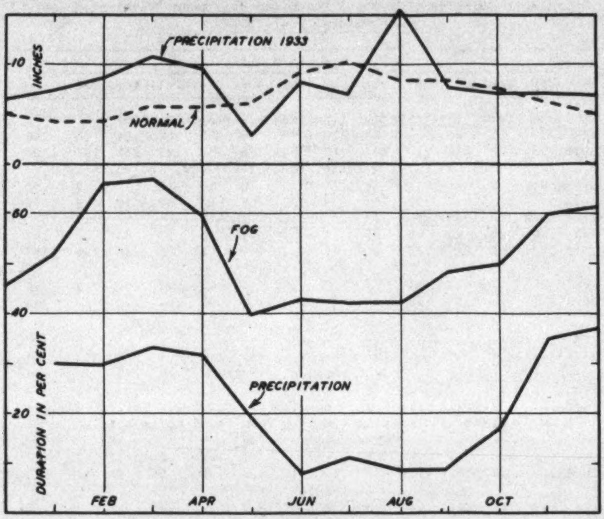


FIG. 4—MT. WASHINGTON (6284 FEET)

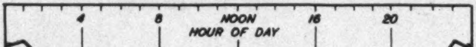


FIG. 5—MOUNT WASHINGTON, NEW HAMPSHIRE (6284 FEET)
DIURNAL VARIATION OF FOG AND PRECIPITATION, 1933

By observing the orientation and length of rime-feathers forming on various parts of the shield, its effectiveness in deviating the air-stream downward and sideways was easily studied [8].

A long series of measurements showed that with wind-velocities up to 30 mi/hr (13 m/sec) the snowfall-coefficient of effectiveness of the shielded gage was 1.34 over a standard unshielded gage located alongside for comparison. With wind-velocities between 30 and 75 mi/hr (13 and 33.5 m/s) the coefficient of effectiveness was 1.69, and with velocities above 75 mi/hr (33.5 m/sec) the effectiveness was 3.00. That is, the catch of the shielded gage was 1.34 to 3.00 times that of the unshielded (see Table 1).

The rainfall-coefficients are, respectively, 1.04, 1.40, and 1.42 (see Table 1).

The effectiveness of the shield is thus seen to increase with the wind-velocity. Precipitation measurements obtained in windy places by means of standard unshielded gages are therefore too low. The normal of 83 inches given for Mount Washington should be properly corrected to allow for the deficiency of the unshielded gage with which this record was obtained. The most satisfactory way of applying this correction would be to classify the precipitation according to type and average wind-velocity at the time precipitation occurred, and multiply by the proper coefficient. A first approximation might be obtained by using an average coefficient obtained from all values independently of the kind of precipitation and of wind-velocity and wind-direction. This coefficient has been calculated to be 1.53 (see Table 1), thus bringing the normal for Mount Washington up to 127 inches.

In order to maintain a constant angle of effectiveness with upward and downward currents, gage and shield should be slanted so that the plane of the orifice is parallel to the slope, as suggested (for the shield alone) by Röstad [8].

The importance of the proper angle of inclination cannot be overemphasized. Too much slant will collect an excessive amount of precipitation with upward currents and a deficient amount with downward currents. Preliminary results of an unshielded snow-gage inclination-test show that a gage on a 5° slope, with the opening slanted in the direction of the slope 5° from the horizontal plane, will collect 40 per cent more precipitation in upward currents than a gage with horizontal opening, and 20 per cent less with downward currentr. A gage slanted 25° down slope will collect 145 per cent more than the horizontal gage with upward currents and 70 per cent less with downward currents. A gage with the orifice in the vertical plane pointed down the slope collected 215 per cent more than the horizontal gage with upward currents and a trace of snow (from eddies) with downward currents.

Table 2 and Figures 4 and 5 present the important facts of annual course of amounts and durations of all kinds of precipitation and of fog, and of the diurnal course of fog and precipitation.

Mount Washington Observatory,
Gorham, New Hampshire

Comment by Charles F. Brooks (contributed)

Mr. Pagliuca does not make clear the reason for slanting the gage, as well as the shield, to the slope. If the orifice of the gage is not slanted, the snowflakes or fine rain ascending the slope with the wind cannot enter the gage, except for turbulence. On a 5° slope, snow will be ascending at wind-velocities exceeding 30 mi/hr (13 m/sec), and 0.3-mm diameter rain-drops will be ascending when wind-velocities exceed 67 mi/hr (30 m/sec). On a 10° slope snow will ascend if the wind exceeds only 15 mi/hr (6 m/sec), fine rain will ascend in upward winds of more than 34 mi/hr (15 m/sec), and ordinary rain (1.0-mm diameter) will ascend if the wind exceeds 67 mi/hr (30 m/sec). These values are based on the table given by Pers [17, p. 110] for the angles of fall of precipitation at different wind-velocities.

To cut the top of the gage on a slant, leaving the gage-can vertical, after Pers [17], would not be altogether satisfactory, for the upward moving snowflakes striking the back of the gage at an obtuse angle would tend to blow out. Since the precipitation is usually measured in terms of depth of water as if spread evenly over a surface equal to the (horizontal) area of the orifice, the catch in a tilted gage should not be referred to the actual area of the orifice, for this is greater than the horizontal projection of the tilted orifice. The catch, measured in the ordinary way as when the orifice is horizontal, should be multiplied by the secant of the angle the orifice deviates from the horizontal.

The catches of the Mount Washington gages have not been multiplied in this way, for only one is standing on a slope, and, on account of the excessive winds and ice, it has not yet been found possible to maintain the gage and shield at the correct angle. Furthermore, other causes of deviation of catch from true fall are so large that this small tilt-correction still seems of minor importance. For the present, however, the measured catches should be considered as under, rather than over, the true precipitation.

Blue Hill Observatory, Harvard University,
Milton, Massachusetts

APPENDIX A--ANNOTATED BIBLIOGRAPHY ON SHIELDED PRECIPITATION-GAGES

Charles F. Brooks and Salvatore Pagliuca
(With acknowledgments to C. F. Talman)

[1] F. E. Nipher, Über die Bestimmung der wahren Regenmenge mittlst hochaufgestellter Regenmesser, Zs. Met., Wien, v. 14, pp. 250-254, 1879; practically same, in German, as paper On the determination of the true rainfall, by elevated gages, Proc. Amer. Assoc. Adv. Sci., St. Louis, 1878, pp. 103-108, Salem, 1879. Nipher proved that a gage protected against wind eddies by an upward flaring shield 3 1/4 inches above the top of the gage would catch as much precipitation at any height as on the ground. The gage was 7.08 cm in diameter, and the shield about 43 inches across. The outer two inches was a horizontal ring of wire screen. The inner portion was metal or wood and covered 1/2 inch above the solid surface by wire screens or vertical bristles to prevent insplashing. The upper part of the flare was at 45°.

[2] R. Börnstein, Über die Bestimmung der wahren Regenmenge mittels hoch aufgestellter Regenmesser, Met. Zs., Braunschweig, v. 1, pp. 381-387, 1884. On roof in Berlin, Börnstein found that unshielded gage caught only 88 per cent of a shielded gage, and that this ranged from 54 per cent with snow to 96 per cent with downpours. The ratio was smallest with the strongest winds, 69 per cent with Beaufort scale 5 and 6, 87 per cent with Beaufort scale 3 and 4, and 92 per cent with Beaufort scale 0 to 2.

[3] H. Wild, Einfluss der Qualität und Aufstellung auf die Angaben der Regenmesser, Repertorium für Met., St. Petersburg, v. 9, No. 9, pp. 1-23, 1885. Differences in catch between gages sheltered by buildings (1869-), by a solid wooden fence (1872-), and by a Nipher shield (1885-), and others exposed in the open showed the need for protection against wind. A Nipher shielded-gage at three meters above the ground caught 29 per cent more than an exposed gage and 2 per cent more than a fenced-in gage.

[4] Hermann Stade, Die Niederschlagsmessungen auf Berggipfeln, Wetter, Berlin, v. 18, pp. 201-205, 1901. On the Brocken, Stade found that gages exposed to the wind caught appreciably less, especially of snow, than those in the lee of the summit-house, but 20 meters from it. The difference increased with the wind-velocity. At Beaufort scale 1 to 2 the catch of rain was the same but of snow only three-fourths as great in the exposed gages; at Beaufort scale 3 to 4 the exposed caught three-fourths of the rain and scarcely half of the snow, and at Beaufort scale 9 to 11 but little over half the rain and less than one-fourth the snow. The sheltered gages caught the same as was obtained by general snow-sampling. Stade concludes that there should be a gage in each of four directions from the summit-house, and that, to take care of occasions when the wind shifts between observation-times, the gages should be heated and recording.

[5] R. Billwiller, Jr., Ein neues Model eines geschützten Regenmessers (abgeanderter Nipherischer Trichter), Met. Zs., Braunschweig, v. 27, pp. 193-198, 1910. Cites Börnstein's, Wild's, and E. Berg's (1895) experiments with shielded gages and remarks that it is peculiar that the Nipher shield has not come into practical use on mountains. For use on mountains, however, Billwiller strengthened the shield, opened the bottom to let the snow fall through, and placed it between two posts so that it could be raised with the deepening of the snow. The shield is 70 cm in upper diameter, 46 cm in lower diameter, and 50 cm high (including 10-cm vertical collar at bottom). In the Gotthard Pass he found that an unshielded gage caught as much rain but only 80 per cent as much snow as the shielded. An exposed gage caught 67 per cent of the shielded at Beaufort scale 0 to 4, and 52 per cent at Beaufort scale 6 or more. A gage more or less sheltered by a building caught 92 per cent in light to moderate winds and 79 per cent in strong winds, of the shielded catch right beside it.

[6] M. de Carle S. Salter, The exposure of rain-gages, being Ch. IV, in Measurement of rainfall, London, 1921. The reduction in catch with elevation above the ground is cited and its relation to angle of rainfall shown. The catch at 25 feet with rain 0° to 35° from the vertical was 90 per cent of that at one foot, with 35° to 40° angle 89 per cent, and with 40° to 75° angle 79 per cent. At Rotherham, experiments with five funneled- and tilting-gages are cited; the five-funneled gage had one horizontal and four vertical orifices--one for each cardinal direction. To reduce the wind-effect to a minimum, England has adopted a gage-height of one foot as standard. Nothing much has been done there with shields. More on the Continent, where there is more snow. Wild's experiments are described, and Norway's pattern (30 inches in diameter at top and 6 inches in diameter at bottom, the size of the gage) and Billwiller's Swiss pattern are also pictured.

[7] H. Ingold, Pluviomètres et pluviométrie, a 1921 paper extracted at length in La Meteorologie, Paris, n.s.v. 8, pp. 77-88, 1932. Description of totalizers for use in mountain regions, with calcium chloride or alcohol to melt the snow and oil to prevent evaporation. No attempt made to shield against wind; in fact, design with large holding tank below small receiver made upward converging slope near orifice, which might increase the wind-error.

[8] A. Röstad, Über die Wirkung des Nipherschen Schutztrichters (a summary of "Verwendung von Nebelfrostablagerungen, um Strömungslinien zu bestimmen," in Geofys. Pub., v. 3, Nr. 2, Kristiania, 1924), Met. Zs., Braunschweig, v. 41, pp. 240-243, 1924. Shows how the air-flows over unshielded square gage and over shielded one, demonstrating that the flow over the gage inside a shield is more nearly horizontal than over the unshielded. With ascending wind, the shield does not provide an even flow, and tends to reduce the catch; with descending wind it may help increase the catch. A mean position, with the shield parallel to the ground, Röstad thinks might make the catch independent of the direction or velocity of wind. The shield used was a truncated square pyramid 72 cm wide and 29 cm high. The diagrams show its sides to be about 40° from the vertical.

[9] A. Röstad, Über die Wirkung des Nipherschen Schutztrichters, Ibid., pp. 266-272. A continuation of the previous study, providing catch-measurements to show the effects. The total catch at the Haldde Observatory for 19 months, 1920-22, of the unshielded gage was 57 per cent that of the shielded, the gage-tops being 1.7 meters above the ground and about 1.4 meters above the snow. They were about 35 meters from buildings, on a gentle southerly slope. With respect to wind-velocity (reduced to values at the height of the gages) the shielded gage caught more relative to the unshielded the higher the velocity, the curve of relationship being parabolic. Of fog-drizzle the shielded gage caught 1.3 times as much as the unshielded at 10 m/sec, of rain and sleet 1.1 at 13 m/sec, of snowfall 2.2 at 16 m/sec; of snowfall and drifting snow, nearly 2.7 at 14 m/sec, though only 2.0 at 20-22 m/sec, a decrease in relative catch because of the outblowing of snow from shielded as well as unshielded gage in such high winds.

[10] Wilh. Hartmann, Über die Wirkung des Nipherschen Schutztrichters, ibid., v. 43, pp. 446-447, 1926. Comments on Röstad's work and cites his own paper "Die Messung der wirklichen Niederschlagsmengen auf Berggipfeln," Wetter, Berlin, v. 37, p. 77, 1920, in which a case on the Feldberg, Schwarzwald, of less catch with a shielded than with unshielded gage is described. The winds here were ascending with great strength. Hartmann recommends experiments in a wind-tunnel to find satisfactory shield, if possible, and apparently overlooks the obvious remedy suggested by Röstad, of simply tilting the shield.

[11] Kofler, reviewing S. L. Bastamoff und W. J. Witkewitsch, Windeinfluss auf Niederschlagsmesser (Les spectres aérodynamiques des pluviometres, Bull. géophys. Inst. Géophys. Moscou, Nr. 10, 1926, in Russian and French), ibid., v. 45, p. 71, 1927. Small models of gages and shields were tested in lycopodium dust in a wind-tunnel to find stream-lines, in a wind of 4 to 5 m/sec. An increased velocity over the gage is shown, even when shielded, the higher velocity covering more than half the diameter of the receiver, which would reduce the catch. The authors suggest as a remedy the use of a flat, solid ring fastened horizontally to the outer edge of the Nipher shield, thus unwittingly coming back to Nipher's original pattern, though his outer ring was of wire netting.

[12] C. E. Brazier, Sur la mesure correcte de la pluie, La Météorologie, Paris, n.s., v. 3, 1927. A French "Association" gage was placed in a flaring shield which had wire netting from the edge of the shield to a cylinder of metal a moderate distance from the gage. This was found to give fairly satisfactory results.

[13] S. Bastamoff, Sur les pluviomètres, ibid., v. 8, pp. 94-98, 1932. Brazier's modification of the Nipher shield and another, called the Nipher shield, were tested in a wind-tunnel with lycopodium dust. Two more models, with a solid filling of smooth wood in place of wire netting (since the netting was detriment in the snowy Russian climate), were also tried. It was found that Brazier's gave the least disturbance of the air-stream over the gage. In fairness to Nipher, however, it should be pointed out that the so-called Nipher shield was below the top of the gage.

[14] C. E. Brazier, Quelques remarques a propos de la note de M. Bastamoff, "Sur les pluviomètres," ibid., pp. 99-101. Brazier describes his shield as differing from the Nipher in only two particulars, that it is level with the gage and that the netting does not extend all the way to the gage. However, Nipher's diagram (1879) showed the gage level with his shield, and the wire netting extending to the gage only along the surface (or rather 1/2 inch above it) of the shield material, and not as a covering across the top. Be this as it may, Brazier gives full credit to Nipher for the aerodynamic performance but calls attention to the fact that there has been no progress in 50 years. There is still a higher velocity across the top of the gage than the actual wind-speed. He says that we cannot assume that the shielded gage gives the correct amount, merely because it gives the most. It might catch too much. He proposes as a test for rain a comparison with a pit-gage, and for snow a comparison with snow on a stone tablet one meter in diameter level with the sod but in the center of a pit three meters in diameter and one meter deep.

[15] M. Philibert, Comparaison entre un pluviomètre-nivomètre "Mougin" protégé et un pluviomètre "Association Ordinaire" au poste du Puy-Chadrac, ibid., pp. 89-91, 3 figs. An indirect test of the sort recommended by Brazier is provided by this comparison between a shielded totalizer which caught 4.5 per cent more than an ordinary gage, while Brazier in 1927 [13] found that a pit-gage caught 4.8 per cent more than an ordinary gage.

[16] R. Pers, Relations entre les données pluviométriques et les precipitations totales recueillies par un bassin: Introduction à l'etude théoretique de la stéréopluviométrie, ibid., pp. 101-106.

[17] R. Pers, Note complémentaire sur la stéréopluviométrie, ibid., pp. 106-113.

[18] A. Boutaric, Les recents progrès des méthodes pluviométriques, La Nature, Paris, No. 2918, pp. 489-494, Dec. 1, 1933.

The three references [16], [17], and [18] call attention to the importance of precipitation received on the vertical component of a sloping surface, which on windward slopes increases appreciably the "rainfall" as defined by the catch in a gage with a horizontal receiver only. Comparing the precipitation on the Grand Som, a 50 per cent slope toward the rain-bearing winds, with that on the Oisans, a similar slope in the opposite direction, the rain-gages show 1900 mm against 900 mm, or 2.1. The actual receipt of water, however, with rain slanting 30° from the vertical, a very moderate amount, found with drops 0.5 mm in diameter and a wind of 2 m/sec (see table, Pers, p. 110), is greater on the windward slope by 29 per cent and less on the leeward by 29 per cent, making the equivalent of 2450 and 640 mm on the horizontal projections of the surfaces, or a ratio of 3.8. The percentage of increase or decrease for the vertical component of the slope is the tangent of the angle of the slope times the tangent of the deviation of the precipitation from the vertical. The precipitation-tangent is the wind-velocity divided by the rate of fall (which ranges from 1 m/sec or less for snow to 8 m/sec for the largest raindrops.

To meet the need for measurement of the vertical as well as the horizontal catch of rainfall, Pers put up ortho-and vectopluviometers, with one horizontal and four vertical orifices. He preferred, however, to avoid the necessary computation by cutting the top and body of the rain-gage to match the actual slopes and outline of that portion of a drainage-basin to be "covered" by the gage. Such gages are in use in the French Dauphiné Alps for the Lake Blanc Basin. Unfortunately, even though these gages were set up on posts about five meters high, no provision was made for shielding against wind.

[19] H. Koschmieder (translated by R. J. Martin), Methods and results of definite rain-measurements, Mon. Weath. Rev., Washington, v. 62, pp. 5-7, 1934. Compares catches of rain in pit-gages against those in ordinary type on Schneekoppe. For the prevention of insplashing the pit-gages were surrounded with discs of brush having vertical bristles or with honeycombs of galvanized iron, having square cells 4 by 4 cm. These protective devices were 1 or 1.5 meters in diameter and level with the ground. The smaller were found to be essentially as effective in preventing insplashing as the larger, and the brush-protected gages caught about the same as the honeycombed. The latter type was considered preferable because it let blowing sand through into the pit and permitted the observer to walk out to the gage without taking up the splash-protector. The pit-gages caught twice as much as the unprotected with upslope winds of 9 m/sec and three times as much with 15 m/sec. The raised gages in rains of fine drops, however, caught more than the pit-gages. A raised gage, protected by a disc of brush parallel to the slope, caught 12 per cent more of the fine rain than the pit-gages in light upslope-winds and 44 per cent more in moderate. The protected pit-gages are useless for snow-measurement.

LAMINAR SHEET-FLOW

Robert E. Horton, H. R. Leach, and R. Van Vliet[a]

Introduction

Laminar sheet-flow may be defined as the flow of a thin sheet of viscous fluid under conditions such that turbulence does not occur.

Direct surface-runoff from the ground takes place initially as the flow of a thin film or sheet of water. Because some of the water is continually being absorbed by the soil and because of the roughness of the ground, the existence of the flowing sheet or film on the ground surface during rain is often overlooked or is barely noticeable. Studies have been made which show that the form and characteristics of the hydrograph of a stream are governed mainly by the phenomena of ground surface-runoff before the water enters definite stream-channels. To determine these characteristics a knowledge of the laws governing the flow of water in thin sheets is necessary.

Surface erosion of soils results from sheet-flow of water and its occurrence is governed in part by the depth and velocity of overland flow during rain.

The phenomenon of flow of water in thin sheets has received little attention and excepting the work of Jeffreys, hereafter cited, no one seems heretofore to have attempted to determine experimentally whether the Hagen-Poiseuille law is verified by actual flow of this type. The purpose of the experiments herein described is to furnish definite information on this point.

Theory of laminar sheet-flow

Let Figure 1 represent the longitudinal profile of a relatively wide channel in which a viscous flow Q, at depth D, is taking place, the channel being level at right-angles to its axis.

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[a] Consulting Hydraulic Engineers, Voorheesville, New York.

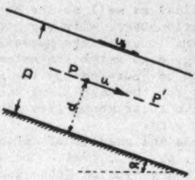


FIG. 1 - LAMINAR SHEET-FLOW

In foot-pound-second units, let: s = the slope of the bottom, sin α; D = the depth from the water-surface to the bottom (feet); d = the distance from the bottom to any point P within the liquid (feet); Q = the total discharge (cubic feet per second); q = the discharge per unit width, Q/width (cubic feet per second per foot); u = the velocity at distance d above the bottom (feet per second); v_s = the surface-velocity (feet per second); v = the mean velocity, q/D (feet per second); ρ = the density (pounds per cubic foot); μ = the absolute viscosity (pounds per second per foot); υ = the kinematic viscosity ($feet^2$ per second) = μ/ρ. Assume that the frictional resistance between the air and water-surface is zero.

For uniform flow, D = constant and there is no acceleration. The accelerating force due to the weight of the water above any plane PP' parallel to the bottom is, therefore, equal to the frictional force acting along the plane. The accelerating force of the weight of the liquid per unit-area above the plane PP' acting parallel to PP' is

$$f = \rho g \, (D - d) \, s \tag{1}$$

The frictional force due to viscous shear per unit of area on plane PP' is

$$-f = \mu \, (du/dd) \tag{2}$$

Equating (1) and (2)

$$\rho g \, (D - d) \, s = \mu \, (du/dd)$$

from which

$$du = (\rho/\mu) \, gs \, (D - d) \, dd$$

and

$$u = (gs/\upsilon) \, (Dd - d^2/2) + C$$

Since with viscous flow, u = 0 at the bottom, where d = 0, C is therefore zero, and

$$u = (gs/\upsilon) \, (Dd - d^2/2) \tag{3}$$

At the surface, d = D and

$$v_s = (gs/\upsilon) \, (D^2/2) \tag{4}$$

The mean velocity is

$$v = (1/D) \, udd = (gs/D\upsilon) \int_0^D (Dd - d^2/2) \, dd = (gs/D\upsilon) \, (Dd^2/2 - d^3/6) \Big|_0^D$$

$$v = (gs/\upsilon) \, (D^2/3) = 10.72 \, (D^2/\upsilon) \, s \tag{5}$$

and from equation (4)

$$v_s = (3/2) \, v \tag{6}$$

Also, as plane PP' approaches the surface the accelerating force due to the weight of the liquid above PP' approaches zero, and hence at the surface equation (1) becomes zero and (du/dd) is zero.

The discharge per unit width is

$$q = vD = (gs/\upsilon) \, (D^3/3) \tag{7}$$

The depth and velocity in terms of q are, from equation (7)

$$D = (3\,\nu q/gs)^{1/3} \qquad (8)$$

and

$$v = q/D = (gs/3\,\nu q)^{1/3}\ q = (gs/3\nu)^{1/3}\ q^{2/3} \qquad (9)$$

and from (6)

$$v_s = (3/2)\ (gs/3\nu)^{1/3}\ q^{2/3} \qquad (10)$$

In English units, for g = 32.16, equations (8), (9), and (10) reduce to

$$D = 0.4535\ (q\nu/s)^{1/3}\text{, in feet} \qquad (11)$$

$$= 5.442\ (q\nu/s)^{1/3}\text{, in inches} \qquad (12)$$

$$v = 2.207\ (s/\nu)^{1/3}\ q^{2/3}\text{, feet per second} \qquad (13)$$

$$v_s = 3.310\ (s/\nu)^{1/3}\ q^{2/3}\text{, feet per second} \qquad (14)$$

Experiments

A series of experiments on sheet-flow was performed at the Horton Hydraulic Laboratory in February 1934. Owing to the conditions prevailing at the time the experiments were made they were carried only slightly beyond the limit of viscous flow.

Experimental flume--The flume consisted of a wooden trough 5.64 inches wide and about 4 feet long, the upper 13 inches of which was used for an approach channel and water-supply inlet. The construction and general arrangement are shown in Figure 2. The bottom was made of 1-inch white pine, which was prevented from warping by 1 1/2 inch angle-iron cleats on the bottom and by angle-iron rails along both sides. It was finished smooth with No. 0 sandpaper but was slightly concave along the axis, being about 0.02 inch low at mid-length. The sides were formed by 1/4 inch by 1 inch white-pine strips, placed between the iron side-rail and the bottom-board. The top edge of the side-angles was 1/2 inch above the bottom and formed the reference-base for all depth-measurements.

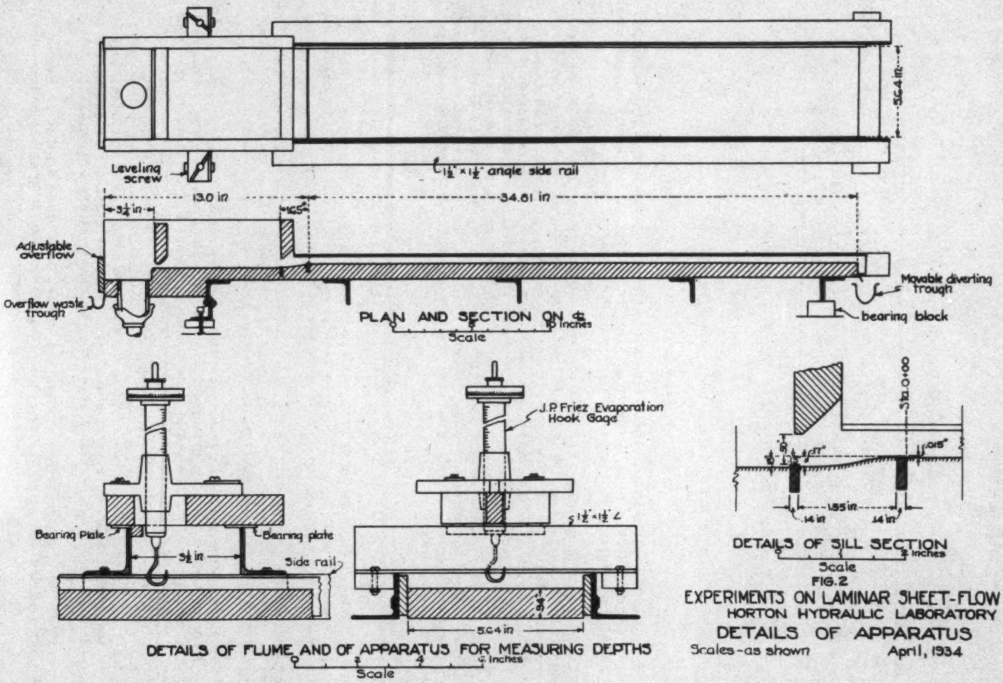
The orifice-gate at the lower end of the approach channel was not used. A brass sill, 1 1/2 inches downstream from and 0.17 inch higher than the gate-sill, marked the beginning of the flume proper. This sill was 0.14 inch wide and projected 0.015 inch above the bottom. This projection did not create any visible disturbance in the measuring reach. The flow was introduced through a vertical pipe 1 1/2 inches in diameter by 3 inches long, at the upper end of the flume.

An adjustable control-weir at the upper end of the flume controlled the height of the water in the intake-pool. The surges due to the upward flow from the well were minimized by a deflector which directed the flow toward the control-weir.

Positions in the measuring reach were determined by means of station and course-lines drawn on the bottom with waterproof ink. Longitudinal course-lines, parallel to the axis, were drawn along the center line and at 1, 2, and 2 1/2 inches on each side thereof, bringing the final lines 0.32 inch from the sides of the flume. They were numbered 1/2, 1, 2, 3, 4, 5, and 5 1/2, from left to right, across the flume.

Stations, in inches, were shown by a scale marked along the center line, beginning at the control-sill and running downstream. Transverse-lines at right-angles to the center line were drawn at 6-inch intervals, beginning at the control-sill.

Positions were designated by station and course, 12-2 being a point 12 inches downstream from the control-sill, on course 2 (1 inch to the left of the center line).



PLAN AND SECTION ON ℄

DETAILS OF FLUME AND OF APPARATUS FOR MEASURING DEPTHS

DETAILS OF SILL SECTION

Leveling screw
$1\frac{1}{2}" \times 1\frac{1}{2}"$ angle side rail
5.64 in
13.0 in
$3\frac{1}{4}$ in
.165"
34.81 in
Adjustable overflow
Overflow waste trough
Movable diverting trough
bearing block
0
5
10 inches
Scale
J.P. Friez Evaporation Hook Gage
$1\frac{1}{2}" \times 1\frac{1}{2}"$ ∠
Bearing Plate
Bearing plate
$3\frac{1}{2}$ in
Side rail
5.64 in
0
2
4
6 inches
Scale
Sta. 0+00
.015"
.17"
1.55 in
.14 in
.14 in
0
1
2 inches
Scale

FIG. 2

EXPERIMENTS ON LAMINAR SHEET-FLOW
HORTON HYDRAULIC LABORATORY
DETAILS OF APPARATUS
Scales-as shown April, 1934

Measurement of depth--The depth was measured by a Fries micrometer hook-gage, mounted as shown on Figure 2. The sliding supports enabled the gage to reach any part of the flume downstream from Station 3.2.

The micrometer-scale on the gage was graduated in 0.001 inch. The depth of water was determined by the difference between the gage-reading at the bottom of the flume and the gage-reading at water-surface, using in both cases the bottom of the curved hook. Readings on the bottom were made by placing a flat brass strip 3/8 by 1 inch on the bottom and slowly lowering the gage until a piece of bond paper placed between the bottom of the gage and top of the brass plate could just be moved. The gage-reading was corrected for the thickness of the brass plate and paper (0.062 inch) to get the true bottom-reading.

Measurements of water-surface were made by slowly lowering the gage until the bottom of the hook touched the water-surface. This contact was distinct and definite, as the instant it was made there was a definite capillary rise on the hook-gage. The hook was wiped dry after each measurement. Repeated measurements rarely differed by more than 0.002 inch and generally by less than 0.001 inch.

Slope--The slope of the side-rail was measured by means of a U-gage. It consisted of two glass tubes, 0.4-inch (internal) diameter by 7 inches long, each mounted on a block and connected by a rubber tube 4 feet long. The gage-tubes were placed 30 inches apart on the side-rails and readings of the water-level in both tubes were taken. The positions of the tubes were then reversed and the readings repeated. The difference in level along the side-rail was obtained from the average difference of the A-readings and the B-readings. The water-level in the tubes could be read to 1/40 inch, equal to a slope of 0.0008 in 30 inches and the probable error in slope is about 0.0004. The effect of this possible error is mainly in the flat slopes.

The hook-gage readings to the bottom of the flume were taken with reference to the side-rails. The slope of the water-surface was obtained by adding algebraically the difference between the water-surface readings at stations 12 and 30 (stations 12 and 24 for runs 1 to 3) to the slope of the channel-bottom.

Volume of outflow--A movable trough was arranged at the downstream end of the flume by means of which the flow through the flume could be instantly diverted into or out of a 25-gallon can. With steady flow established, the discharge through the flume was caught in the can for a period of 10 to 30 minutes. The outflow was weighed on a Fairbanks silk scale, capable of weighing to 1/4 ounce. The discharge in a given experiment usually weighed from 100 to 200 pounds. Under these conditions extreme accuracy in the determination of the volume of outflow was attainable.

Measurement of surface-velocity--The surface-velocity was determined by the time of transit of the front of a patch of color over the 24 inches between stations 6 and 30. After trying fluorescein and various other materials, ordinary washing-bluing was adopted. This gave a distinct, easily observed color-patch. The bluing was dropped on to the surface near Station 2, from the needle of a hypodermic syringe, held about 0.1 inch above the water-surface. Observations were made with a stop-watch graduated in 1/5 seconds.

Several comparisons made with circular paper-floats, 1/8 inch in diameter, dropped on the surface from the point of a knife, gave velocities in good agreement with the front of the color-patch, as the following tabulation shows.

Course No.	Time in seconds Color	Time in seconds Paper
3 (center line)	5.4	5.6
	5.4	5.4
	5.4	5.4
5 (2 inches right of center line)	5.0	5.0
	4.9	5.0
	4.9	5.0
5.5 (0.32 inch from side)	4.8	4.8
	5.0	4.8
	5.0	4.8

From 15 to 30 velocity-observations were made for each run. With a probable error of 0.2 second in observed time, single observations were subject to an error of 20 per cent in the case of the highest velocities, decreasing to 4 per cent for the lowest velocities. The error in mean velocity for a run probably did not exceed 5 per cent in any case.

Experimental procedure and observations--Before turning water into the flume for a series of runs, hook-gage readings were taken on the bottom, generally at all points where depths were to be read. The amount of swelling of the wooden flume was determined by repeating these measurements at the end of a series after the water had been turned out of the flume. The swelling did not exceed 0.008 inch at any point and usually averaged less than 0.005 inch. The observations indicated that all or nearly all of the swelling occurred during the first and second runs.

The flume was then leveled transversely and the longitudinal slope measured. The flow was started and the end-weir adjusted so that there was a slight flow over the weir. At a given time the outflow was diverted into the measuring can and readings of the water-surface were taken at 6-inch intervals along the center line, beginning with Station 6, together with readings at Station 3.2 and 34.0. In addition, readings on courses 1 and 5 were generally taken at stations 12, 18, and 30 to determine the transverse-variation in depth.

Velocity-observations were then made, taking three readings (frequently more and occasionally only two) along each of the five courses. Temperature-readings of the water were taken from time to time in the inflow-pool during the course of the run. There was generally little or no change in the temperature of the water. When readings were completed, diversion into the can was stopped and the water was weighed.

With the lower flows the surface was smooth. At the higher flows stationary ripples projected diagonally downstream from each side of the flume and in certain cases cross-ripples projecting both upstream and downstream were formed.

Attempts were made to obtain color stream-lines by introducing a steady flow of color from the syringe-needle projecting below the surface. At the lower velocities some of these were fairly successful and produced thin threads of color of uniform size and intensity. The path was generally more or less sinuous, although the thread was unbroken and of uniform size throughout its length. At high velocities, turbulence at the needle made it difficult to obtain a thin thread and the color-stream appeared as a broad, sinuous band.

Excluding preliminary trials, 28 runs were made, in the first four of which the flow contained more or less entrained air.

Table 1 gives the observed or experimental data for each run. Columns 5 to 9, inclusive, give the average of all of the depths, in inches, measured at different points on the section at the designated station. Column 10 gives the arithmetic average of the mean depths at stations 12, 18, 24, and 30. Columns 11 to 15, inclusive, give the measured surface-velocities on five lines or courses at distances from the left-hand side of the flume, as indicated in the column-headings. Observations taken on two additional courses, one inch each side of the center line, as a check on the center-line velocity, gave velocities nearly the same as those observed at the center line. The average surface-velocity as given in column 16 was obtained from the mean velocities of all seven courses, including the two adjacent to the center line, but giving the observations for the side-courses (0.5 and 5.5) half the weight of the other observations.

The kinematic viscosities given in column 19 in foot-pound-second units are based on the following data:

Temperature °F	υ	Temperature °F	υ
30	0.0000200	60	0.0000121
40	0.0000167	70	0.0000106
50	0.0000141	80	0.0000093

TABLE 1-EXPERIMENTAL DATA, LAMINAR SHEET-FLOW

Date 1934	No.	Slope Sta. 12 to 30		Measured Depth Inches at station					Average Depth Sta. 12 to 30 Inches D	Measured Surface-Velocity Ft per Sec.					Mean Surface Velocity Sta. 6 to 30 u_s	Discharge Cu ft/sec per ft width q	Temp. Water °F θ	Kinematic Viscosity ft²/sec ν
		Flume	Water-Surface s	6	12	18	24	30		.5 2½" left	1 2" Left	3 Center Line	5 2" Right	5.5 2½" Right				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Feb. 1	1	.0123	.0104		.0785	.0830	.0843		.0819	.555	.500	.527	.588	.625	.543	.00249	41.9	.0000 .1615
"	2	"	.0114		.0950	.0993	.0970		.0971	.740	.800	.765	.833	.909	.804	.00236	43.4	1575
"	3	"	.0115		.1027	.1047	.1060		.1045	.930	.908	.930	.975	1.000	.951	.00533	46.4	1520
Feb. 5	4	.00667	.00539	.1610	.1510	.1608	.1610	.1630	.1588	.852	.862	.930	.908	.908	.908	.00824	43.4	1575
Feb. 7	5	.00667	.00562	.1677	.1500	.1533	.1610	.1607	.1578	.897	.922	.858	.897	.869	.892	.00684	32.6	1910
"	6	.00375	.00264	.1250	.1223	.1335	.1345	.1345	.1312	.672	.714	.672	.689	.697	.689	.00487	"	"
"	7	"	.00208	.1130	.1150	.1245	.1275	.1360	.1258	.583	.588	.560	.560	.601	.569	.00386	"	"
"	8	.00646	.00396	.0960	.1020	.1135	.1210	.1370	.1184	.392	.362	.370	.406	.406	.381	.00242	"	"
"	9	"	.00557	.1560	.1497	.1585	.1555	.1550	.1557	.833	.823	.870	.867	.880	.846	.00751	"	"
Feb. 12	10	.00642	.00548	.1420	.1380	.1460	.1469	.1483	.1446	.832	.858	.832	.832	.832	.838	.00615	32.8	1905
"	11	"	.00553	.1770	.1647	.1630	.1700	.1723	.1690	1.000	.965	1.000	1.000	1.000	.995	.00966	"	"
Feb. 15	12	.0104	.0106	.1620	.1507	.1487	.1470	.1480	.1486	1.250	1.177	1.130	1.198	1.198	1.163	.00984	32.6	1910
"	13	"	.0100	.1430	.1340	.1343	.1350	.1360	.1348	1.070	1.053	.966	1.036	1.000	1.015	.00803	"	"
"	14	"	.0097	.1050	.1043	.1053	.1080	.1080	.1074	.810	.790	.714	.769	.833	.759	.00486	32.8	1905
"	15	"	.0088	.0810	.0830	.0873	.0860	.1013	.0894	.551	.555	.457	.517	.545	.504	.00245	33.4	1865
"	16	.0127	.0115	.0770	.0780	.0817	.0800	.0893	.0822	.588	.537	.476	.545	.600	.523	.00243	33.3	1880
"	17	"	.0121	.1080	.1053	.1077	.1060	.1063	.1063	.908	.832	.790	.843	.890	.840	.00896	32.8	1905
"	18	"	.0124	.1440	.1340	.1300	.1290	.1293	.1306	1.111	1.156	1.037	1.156	1.111	1.121	.00878	32.6	1910
"	19	"	.0128	.1560	.1483	.1423	.1360	.1363	.1407	1.212	1.157	1.191	1.191	1.228	1.187	.01012	"	"
Feb. 22	20	.0123	.0125	.1365	.1220	.1190	.1160	.1170	.1185	1.110	1.000	1.000	1.000	1.000	1.010	.00747	52.3	1368
"	21	"	.0125	.1700	.1540	.1500	.1430	.1450	.1480	1.177	1.250	1.250	1.250	1.250	1.244	.01400	35.7	1805
"	22	"	.0131	.2060	.1890	.1810	.1710	.1690	.1775	1.370	1.540	1.540	1.430	1.250	1.447	.01577	35.5	1815
"	23	.0196	.0204	.1840	.1640	.1550	.1470	.1450	.1528	1.539	1.667	1.539	1.430	1.430	1.543	.01938	36.6	1780
"	24	.0358	.0365	.1530	.1310	.1270	.1140	.1140	.1215	1.905	2.220	2.000	—	—	1.980	.01641	35.1	1825
"	25	"	.0355	.0770	.0763	.0750	.0730	.0750	.0748	1.430	1.250	1.250	1.430	1.430	1.340	.00617	36.5	1815
"	26	"	.0355	.0860	.0780	.0810	.0750	.0790	.0782	1.540	1.430	1.430	1.430	1.670	1.400	.00716	36.0	1800
"	27	.0467	.0474	.1340	.1180	.1140	.1040	.1020	.1095	2.000	2.220	2.000	2.000	2.000	2.037	.01588	34.9	1835
"	28	"	.0471	.0730	.0670	.0730	.0690	.0710	.0700	1.670	1.430	1.250	1.430	1.540	1.383	.00663	35.4	1820

TABLE 2-RESULTS OF EXPERIMENTS

Expt. No.	Mean Depth Sta. 12 to 30 feet D	Slope of Water Surface s	Kinematic Viscosity ν	Mean Surface-Velocity Sta. 12 to 30 u_s	$\frac{2}{3} u_s$	q/D	Mean of Cols. (6) & (7)	Ratio Col. (7) to Col. (8)	Calculated Velocity for Laminar flow u_1	Calculated Velocity for Turbulent flow u_t	Reynolds Number q/ν	Type of Flow
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	.00683	.0104	.00001615	.543	.362	.365	.364	.672	.320	.606	154	Laminar
2	.00809	.0114	1575	.804	.536	.292	.414	.363	.509	.709	150	"
3	.00871	.0115	1520	.951	.634	.612	.623	.644	.617	.747	350	"
4	.01322	.00539	.00001575	.908	.606	.623	.614	.686	.641	.678	523	Laminar
5	.01315	.00562	.00001910	.892	.594	.528	.561	.592	.546	.688	364	Laminar
6	.01093	.00264	"	.689	.460	.446	.453	.647	.177	.417	255	"
7	.01048	.00208	"	.569	.380	.368	.374	.647	.126	.356	202	"
8	.00987	.00396	"	.381	.254	.245	.250	.643	.218	.478	127	"
9	.01298	.00557	"	.846	.564	.579	.572	.684	.528	.684	394	"
10	.01206	.00548	.00001905	.838	.558	.510	.534	.609	.450	.642	323	Laminar
11	.01408	.00553	"	.995	.664	.686	.675	.689	.618	.714	507	"
12	.01238	.0106	.00001910	1.163	.776	.795	.786	.684	.913	.909	515	Laminar
13	.01122	.0100	1910	1.015	.676	.715	.696	.704	.707	.825	421	"
14	.00895	.0097	1905	.759	.506	.508	.507	.669	.438	.702	239	"
15	.00745	.0088	1865	.504	.336	.329	.333	.653	.278	.551	130	"
16	.00685	.0115	1880	.523	.348	.354	.351	.677	.306	.639	129	"
17	.00886	.0121	1905	.840	.560	.605	.583	.720	.535	.777	281	"
18	.01088	.0124	1910	1.121	.748	.807	.778	.720	.824	.904	460	"
19	.01172	.0128	1910	1.187	.792	.862	.827	.726	.987	.964	530	"
20	.00988	.0125	.00001368	1.010	.674	.756	.715	.749	.960	.849	548	Laminar
21	.01232	.0125	1805	1.244	.830	1.136	1.136[a]	.918	1.130	.983	773	Turbulent
22	.01480	.0131	1815	1.447	.964	1.066	1.066[a]	.737	1.700	1.139	867	"
23	.01272	.0204	1780	1.543	1.028	1.521	1.521[a]	.985	1.994	1.285	1088	"
24	.01012	.0365	1825	1.980	1.320	1.621	1.621[a]	.819	2.200	1.476	898	"
25	.00623	.0355	1815	1.340	.894	.990	.942	.739	.815	1.053	340	Laminar
26	.00652	.0355	1800	1.400	.934	1.100	1.017	.786	.900	1.083	397	"
27	.00913	.0474	1835	2.037	1.358	1.685	1.685[a]	.828	2.310	1.570	837	Turbulent
28	.00588	.0471	1820	1.383	.922	1.138	1.030	.822	.943	1.160	364	Laminar

(a) Turbulent Flow, q/d used.

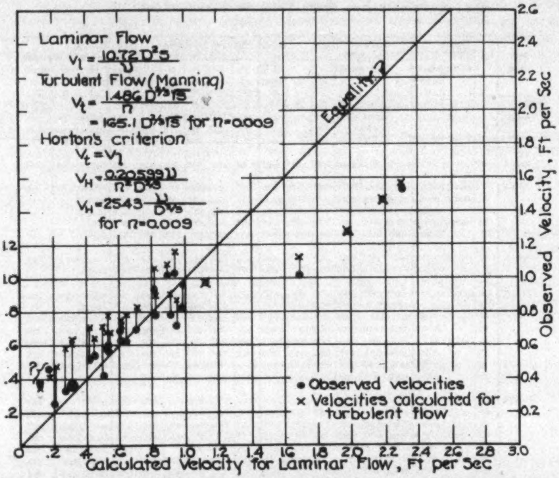


FIG. 3 - COMPARISON OF OBSERVED AND CALCULATED VELOCITIES FOR LAMINAR AND TURBULENT FLOW

Results of the experiments

Table 2 gives the results of the experiments with the depth (column 2) expressed in feet. From equation (6) it will be seen that for laminar sheet-flow the mean velocity is two-thirds of the surface-velocity. Since the discharge q per foot of width and the depth D are known, the experimental data afford two methods of determining the mean velocity where the flow was laminar. The mean velocities, as determined, respectively, from the surface-velocity and from the discharge and depth, are given in columns 6 and 7. Since these two results appear to be about equally reliable, the average of the two, as given in column 8, has been used in cases where the flow was definitely non-turbulent. Experience in connection with turbulent flow in open channels shows that the ratio of mean velocity to surface-velocity is higher than for laminar flow. For turbulent flow the ratio is usually 0.75 to 0.90. The ratio of the mean velocity, determined from discharge and depth, column 7, to the surface-velocity, column 5, is given in column 9. These ratios afford a criterion for determining in which cases the flow became turbulent. It will be noted that for experiments 1 to 20, inclusive, the ratio of the surface-velocity to the mean velocity is always less than 0.75 and, with a few exceptions, close to two-thirds, indicating that in all these experiments the flow was distinctly laminar. Also it will be noted that with the exception of experiments 6 and 7, the calculated velocity for laminar flow, as given in column 10, is generally in good agreement with the observed mean velocity, given in column 8.

Column 11 of Table 2 gives the calculated velocity for turbulent flow, assuming a value of Manning's roughness coefficient n = 0.009.

Figure 3 shows by black dots the observed mean velocities plotted in terms of the calculated velocities for laminar flow. For the first 20 experiments, excepting numbers 6 and 7, the plotted points generally fall close to the line of equality. Crosses plotted on the same diagram show the velocities as they would be for turbulent flow.

For reasons subsequently explained, the velocity of turbulent flow, if such flow could occur at very slight depths, would be greater than the velocity of laminar flow. It will be noted that for velocities less than one foot per second the calculated velocities for turbulent flow are above the line of equality. They are also generally higher than the observed velocities. For experiments 6 and 7 the calculated velocities for turbulent flow and the observed velocities are in agreement. This of itself would indicate that in these cases the flow was turbulent. A similar result might, however, be obtained by an error in the measurement of slope. [Reduction of one-half in the measured slope in experiments 6 and 7 would bring these points into harmony with the other data and would also bring them below the calculated velocities for turbulent flow at the corrected slope.] At the time the experiments were made and in advance of the calculations, it was noted that the measured slope for these two experiments was apparently in error. Both the ratio of mean velocity to surface-velocity and the appearance of the water-surface during the experiments indicate that the flow was, in fact, distinctly laminar in these two cases.

With reference to experiments 20 to 28, inclusive, several of these are for velocities close to unity. In this region some fall above and some below the line of equality. Lines added to the diagram connecting the observed velocities with the calculated velocities for turbulent flow show that in every instance where the calculated velocity is close to but below one foot per second, the observed velocity is materially below the velocity for turbulent flow. It appears reasonably certain that in every instance where the observed velocity was less than one foot per second the flow was definitely laminar.

In case of experiments numbers 21 to 24, inclusive, and number 27, the observed velocities were materially in excess of one foot per second. In all these cases the ratio of surface to mean velocity equals or exceeds 0.73 and in all these cases the observed mean velocity is in good agreement with the calculated velocity for turbulent flow.

For conditions where the flow is definitely laminar, the mean velocity for sheet-flow, as given by equation (5), is confirmed by the experiments and this equation, which has heretofore had little more than a theoretical basis, can apparently be accepted as reliable for determining the velocities of laminar sheet-flow on smooth surfaces. Theoretical considerations indicate that the velocity of laminar flow in accordance with Poiseuille's law is independent of the roughness of the surface. Whether this is or is not true in fact remains to be determined from additional experiments.

Reynolds' criterion

The general expression for the resistance to the flow of fluids in pipes is

$$R = \rho v^2 \ f \ (vd/\upsilon) \tag{15}$$

in which (vd/υ) is the Reynolds number. In a wide channel the linear dimension represented by the diameter, d, of the pipe may be replaced by the depth of water, D, and equation (15) becomes

$$R = \rho v^2 \ f \ (vD/\upsilon) \tag{16}$$

or, since $vD = q$

$$R = \rho v^2 \ f \ (q/\upsilon) \tag{17}$$

Jeffreys (Harold Jeffreys, The flow of water in an inclined channel of rectangular section, Phil. Mag., s. 6, v. 49, No. 293, London, May 1925) has suggested that (q/υ) be called the Reynolds number, since both q and υ are under direct control. Each form has advantages, depending on the problem.

In steady flow, with no acceleration, R per unit-area of channel is measured by the component of the weight of water parallel to the bottom of the channel. Then $R = \rho g$ DS, and, from equation (16)

$$(gDs/v^2) = f \ (vD/\upsilon) \tag{18}$$

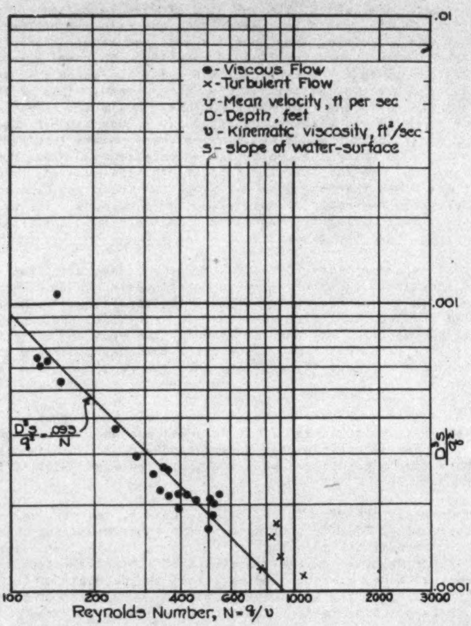


FIG.4-REYNOLDS NUMBER FOR SHEET-FLOW EXPERIMENTS

and as $v^2 = (q^2/D^2)$

$$(gD^3s/q^2) = f\ (vD/\nu) \tag{19}$$

When the flow is viscous, $f\ (vD/\nu)$ can be determined from equation (5), which, when both sides are multiplied by D^2v, becomes $D^2v^2 = (D^3gs/3)\ (vD/\nu)$, which is equivalent to

$$(3q^2/D^3gs) = (vD/\nu) \tag{20}$$

Therefore as long as the flow is viscous, (D^3s/q^2) is inversely proportional to the Reynolds number, (vD/ν).

Values of Reynolds number for the authors' experiments are given in column 12, Table 2. The observed values of (D^3s/q^2) and (vD/ν) are plotted on Figure 4. The line shown is the graph of equation (20), which reduces to $(D^3s/q^2) = 0.0933/N$, in which N is the Reynolds number, (vD/ν) or (q/ν).

The experiments in which the flow was viscous follow the line of the equation rather closely but in general somewhat below it. This is due in part, at least, to side-effect. In runs 25 and 26 (Reynolds number 340 and 395) the capillary rise on the sides was noticeably greater than in most of the runs and the velocity for a distance between 0.2 and 0.3 inch out from the side was much higher than that of the main sheet. As a result an unduly large proportion of the flow travelled close to the sides, reducing the depth in the body of the sheet below what it would have been with a wider channel and the same discharge per foot of width.

Jeffreys found that for sheet-flow, turbulence set in when the Reynolds number was about 310 and states that Hopf obtained critical values between 300 and 330. Referring to column 12, Table 2, it will be noted that the highest value of Reynolds number in any of the authors' experiments in which the flow was definitely laminar is 548. The lowest value of Reynolds number in any of the experiments in which the flow was turbulent is 773. For reasons given in the next paragraph, the authors believe that Reynolds number, taken by itself, is not a reliable criterion of the point at which flow changes from a laminar to a turbulent regime or vice versa.

Horton's criterion

Osborne Reynolds, as a result of experiments on pipes, concluded that there are two limits between which the flow in pipes may be either laminar or turbulent, these limits depending only on the pipe-diameter and the viscosity of the fluid. There is some question as to the applicability of Reynolds' criteria for pipes in the case of open channels. Furthermore, the pipes on which Reynolds experimented were relatively smooth and there is a question as to the validity of his results with reference to flow over rougher surfaces.

The velocity of laminar sheet-flow varies as the square of the depth D. The velocity of turbulent flow in a wide channel varies as the two-thirds power of the depth. The squares of small numbers are still smaller numbers, while the two-thirds power of a small number is a larger number. It follows that at very slight depths the velocity of turbulent flow, if it could occur, would be greater than the velocity of laminar flow, as is shown, for example, on Figure 3. For a given channel-roughness, temperature, and slope there is always some depth at which the velocities of laminar and turbulent flow would be equal. For smaller depths the velocity of laminar flow is less than would be the velocity for turbulent flow if the latter could occur.

Before the experiments above described were undertaken the senior author was engaged in a study of velocity and energy-distribution in channels and concluded that turbulent flow cannot occur below the depth at which the velocities for both types of flow are the same, for the reason that the stream does not contain sufficient energy to sustain turbulent flow at smaller depths. The energy of laminar flow is all energy of translation. When the flow is turbulent the fluid contains both energy of translation and rotational energy. From the analysis of velocity-distribution in channels, above described, it was found that when the velocities for laminar and turbulent flow are equal, the total energy per unit-volume of fluid, including both translational and non-translational energy for turbulent flow, is nearly identical with the translational energy per unit-volume for laminar flow. At or near the point of equal velocities the flow may, therefore, be either laminar or turbulent, or change from one to the other without any change in energy, but laminar flow cannot become turbulent flow at lower velocities. At higher velocities laminar flow may persist but the energy-content of the water is greater than that required to sustain turbulent flow. A change from laminar to turbulent flow can take place apparently at any velocity exceeding the point of equal velocities, but if it takes place at a higher velocity it will be accompanied by a surge or change of water level in the channel. The point of equal velocities apparently fixes the lower limit of turbulent flow in a channel. The position of this point can be determined as follows. From equation (5) the velocity of laminar flow is

$$v_\ell = 10.72\,(D^2/\nu)s \tag{21}$$

According to the Manning formula the velocity for turbulent flow in a wide channel, where side influence may be neglected, is given by the equation

$$v_t = (1.468/n)\,D^{2/3}\sqrt{s} \tag{22}$$

where n is the coefficient of roughness of the channel. Both formulas are in foot-pound-second units. Equating the right-hand members of these equations and simplifying gives

$$7.214\,(n/\nu)\,D^{4/3}\sqrt{s} = 1 \tag{23}$$

According to this analysis the flow cannot be turbulent if the left-hand member of equation (23) is less than unity. Equation (23) may be written in the form

$$D^{2/3}\sqrt{s} = \upsilon/7.214\ nD^{2/3} \tag{24}$$

Since the value of $D^{2/3}\sqrt{s}$ appears as one of the factors in the Manning formula, the substitution of the value of this quantity from the right-hand member of equation (24) in equation (22) gives as the Horton criterion

$$v_H = 0.206\ \upsilon/n^2\ D^{2/3} \tag{25}$$

or, roundly,

$$v_H = \upsilon/5\ n^2\ D^{2/3} \tag{26}$$

Reynolds' criterion for pipes may be written in the form

$$v_R = k\ (\upsilon/D) \tag{27}$$

It will be seen that there is a close similarity between this and the Horton criterion for open channels. In the latter the depth appears inversely, with an exponent 2/3 instead of unity; also the Horton criterion contains the roughness-coefficient n, whereas Reynolds' criterion does not involve the roughness of the channel.

Since the velocities of laminar and turbulent flow are different functions of D and s, and the former involves kinematic viscosity, while the latter involves roughness, it follows that the ratio of the two velocities is not a continuous one-value function of depth and viscosity. For the same depth and viscosity the ratio has different values, depending upon the slope and roughness of the channel. If an average line (not shown on the diagram) is drawn on Figure 3 through the points corresponding to turbulent-flow velocities, it will be noted that this line crosses the line of equality very close to the point corresponding to unit velocity; in other words, the experimental data shown on Figure 3 indicate, as does the Horton criterion, that the flow is laminar for velocities below that corresponding to the point where the velocity-lines for laminar and turbulent flow intersect. It will also be noted that the flow was definitely turbulent only in cases where the velocity for turbulent flow was less than would have been the velocity for laminar flow. Furthermore, in every case where the actual or measured velocity was less than that corresponding to the point of equal velocities for laminar and turbulent flow, the flow was distinctly laminar. For cases where the flow was distinctly turbulent, the measured velocity is in excellent agreement with the calculated velocity for turbulent flow. The experimental data therefore afford a confirmation of the Horton criterion.

It is to be noted, however, that in these experiments the depth and velocity were built up in all cases from zero and with initially laminar flow; also that only one type of surface was used, this having a coefficient of roughness n = 0.009. It is, of course, desirable that the experiments should be repeated; also that experiments should be made using the reverse procedure, that is, starting with definitely turbulent flow and decreasing the depths to the point required for the given experiment; also that experiments should be made on surfaces with different degrees of roughness.

The question of the existence of an upper limit of laminar sheet-flow remains open. It may be noted that the analysis of velocity and energy-distribution in channels by the senior author, above referred to, does not indicate any definite upper limit of laminar flow. Details of this matter cannot be presented here in full. It is expected that the results of this investigation will be separately published in the near future.

Voorheesville, New York,
May 1, 1934

TESTS OF PERMEABILITY WITH LOW HYDRAULIC GRADIENTS

O. E. Meinzer and V. C. Fishel

Problem investigated--The rate of flow of water through any given permeable material containing only small openings varies directly as the hydraulic gradient. This is essentially the law announced by Darcy in 1856 as a result of his experiments with the flow of water through sand. The principle as applied to flow through capillary tubes was, however, announced by Poiseuille in 1843. Since 1856 many careful investigations have been made of the flow of water and other fluids through permeable materials, and the results of these investigations have thoroughly demonstrated the essential accuracy of Darcy's law for a wide range of hydraulic gradients. In the tests that have been made in the Hydrologic Laboratory of the United States Geological Survey on about 1000 water-bearing materials it has been customary to determine the permeability of each sample under several heads, and thus even the routine work in our Laboratory furnishes a great amount of evidence supporting Darcy's law. [For a brief historical statement of this subject, with references, see U. S. Geol. Sur. Water-Supply Paper 638, pp. 131-134.]

Presumably Darcy's law holds because the flow through small openings (known as "capillary openings") is laminar flow. The flow through materials having larger openings (known as "supercapillary openings") does not follow Darcy's law, presumably because the flow changes in character from laminar to turbulent. There is no definite limit to the size of capillary openings, because velocity as well as size is a factor in producing turbulence.

Investigations of the viscosity of water at very low velocity gradients have been made by A. W. Duff in 1905, L. E. Gurney in 1908, and A. Griffiths and C. H. Knowles in 1912. [For bibliography see Emil Hatschek, The viscosity of liquids, London, 1928, p. 62.] The results of these investigations apparently indicate that the viscosity does not change at low velocity gradients, and hence they create a presumption that Darcy's law holds for flow through permeable materials under low hydraulic gradients.

Some hydrologists, however, have expressed the belief that under very low hydraulic gradients the flow through water-bearing materials is much less than would be required by Darcy's law or may even cease entirely. Thus, T. A. Miller-Brownlie (Subsoil water in relation to tube-wells, Indian and Eastern Engineer, 1919, pp. 191-193), in his observations on the flow of water in the subsoil of the Punjab, decided that there was no apparent motion in moderately coarse sand with gradients of less than 20 feet to the mile or in fairly fine sand with gradients of less than 30 feet to the mile. Many of the water-bearing formations in the United States have gradients of much less than 20 feet to the mile, and some may have gradients of less than one foot to the mile, whereas most of the laboratory tests of permeability have been made with much higher gradients. It therefore became necessary to investigate the law of flow through water-bearing materials under low gradients.

Previous work--When the Hydrologic Laboratory was organized in 1923, a series of permeability tests with low gradients was made by Norah Dowell Stearns under the direction of the senior author of this paper (Water-Supply Paper 596, pp. 144-159). The tests were made on a sand from Fort Caswell, North Carolina, having an effective size of 0.14 mm and a uniformity coefficient of 1.9. The results agreed closely with Darcy's law down to a gradient of about five feet to the mile, below which the results were erratic because of losses through evaporation and perhaps also because of variations in temperature.

Apparatus used--Two general types of permeability apparatus are used in the Hydrologic Laboratory, which may be called the "discharging" and the "non-discharging" types. Each type comprises a supply-reservoir, a receiving reservoir, and a connecting conduit containing the sample of material through which the water passes from the supply-reservoir to the receiving reservoir. In an apparatus of the discharging type the water-level in the receiving reservoir remains constant, and the overflow, which is measured or weighed, represents the quantity of water that has flowed through the material in any given period. In an apparatus of this type the water-level in the supply-reservoir is raised or lowered from time to time but is maintained at a given level long enough to determine the rate of flow under the resulting head. In an ap-

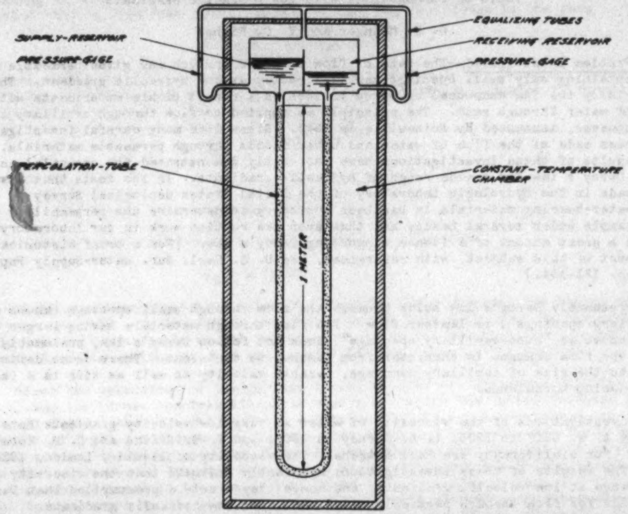


Fig. 1--Diagram showing non-discharging apparatus used in this investigation

paratus of the non-discharging type the test is started with the water-level in the supply-reservoir at any desired height above the water-level in the receiving reservoir. As water flows through the sample the water-level declines in the supply-reservoir and rises in the receiving reservoir, with the result that the head which causes the flow diminishes continuously but at a decreasing rate. In an apparatus of this type the only observations that are required are the differences in the water-levels at stated times, the quantities of flow during the intervals between successive observations being computed from the changes in water-levels and the cross-sectional areas of the reservoirs.

The investigation of 1923 was made with an apparatus of the discharging type in which the water flowed upward through a column of sand one meter in height. In the present investigation an apparatus of the non-discharging type was used (Fig. 1). The conduit in this apparatus is a U-tube made from a 3/4-inch copper pipe eight feet in length. The pipe was bent so that the two columns of the U-tube are about four inches apart. The total length of the sample of sand used in this investigation was two meters. The reservoirs are made of copper sheeting and are six inches square. They are tightly covered to prevent evaporation but are connected at the top to insure equal air-pressure on the two water-surfaces. A compartment with lower walls, two inches square, was built in the bottom of each reservoir. By keeping the water-levels above the tops of the small compartments, the 6-inch reservoirs may be used, and by lowering the water-levels the 2-inch reservoirs may be used. Glass pressure-tubes are connected with each of the reservoirs, and the differences in water-levels are read with the cathetometer that was used in the investigation of 1923. The original tubes were one centimeter in inside diameter, but tubes 1.7 centimeters in diameter were later substituted. The entire apparatus, except the pressure-tubes, is enclosed in a constant-temperature chamber, which is kept at a temperature slightly higher than the maximum room-temperature. The tubes are connected above with the reservoirs by rubber tubing, to prevent evaporation and to equalize the air-pressure in the tubes with that in the reservoirs. Distillation of the water from the reservoirs into the tubes is prevented by inserting a capillary tube in the rubber tubing connecting them.

Method of computing permeability--The permeability of any material tested in an apparatus of the non-discharging type, in which the water rises in the receiving reservoir while it falls in the supply-reservoir, can be computed by means of the following general formula, which was developed by C. V. Theis

$$P = [K\ A\ B\ L/(A + B)\ at]\ \log_e\ (h_1/h_2)$$

in which P is a coefficient of permeability, K is a constant, A and B are the respective areas of the water-surfaces in the supply and receiving reservoirs, L is the length of the column of material through which the water flows, a is the area of cross-section of the column of material, t is the duration of the period between the times at which any two sets of observations of the water-levels were made, and h_1 and h_2 are the respective differences in water-levels, or effective heads, at these two times. This formula makes no correction for temperature, and none was made in the present investigation, because the purpose was merely to obtain comparative results at any constant temperature.

The coefficient of permeability that has been used in the Hydrologic Laboratory since 1923, as defined in Water-Supply Paper 596, page 148, is expressed by the rate of flow, in gallons a day, through a square foot of the cross-section of the material tested, under a hydraulic gradient of 100 per cent at a temperature of 60° F. To compute the coefficient of permeability of a material tested in the apparatus used in this investigation, the formula given above may be expressed as follows, provided L is equal to two meters and t is expressed in minutes, no correction being made for temperature. The quantities h_1 and h_2 may obviously be expressed in any units.

$P = (6,333,000/t) \log_{10} (h_1/h_2)$, if the 6-inch reservoirs and 1.0-centimeter pressure-tubes are used, as in test 2, and $P = (763,000/t) \log_{10} (h_1/h_2)$, if the 2-inch reservoirs and 1.7-centimeter pressure-tubes are used, as in test 8.

Results of the investigation--Work with the non-discharging apparatus was begun August 3, 1933, and has been continued to the present time. During this time eight fairly successful tests have been run. The first six were run with the 6-inch reservoirs and required from 16 to 29 days each, observations generally being made once a day. The last two, made with the 2-inch reservoirs, required less time and gave equally good results.

The material used was Fort Caswell sand obtained from the same supply as that used in the investigation of 1923. The same sample was used for all eight tests without removal or molestation of any kind. Certain precautions were taken to prevent clogging of the sand with air-bubbles or by the growth of bacteria or algae. The coefficient of permeability of the Fort Caswell sand as determined in 1923 is 415. The sand was not as closely packed in the present investigation as it had been in the earlier one, and probably for this reason the coefficient of permeability was about 700 at the beginning and declined to about 400 by the middle of October, after which it remained nearly constant until March. After about the middle of March the coefficient of permeability declined to only about 200, probably on account of clogging of the sand by some unknown cause. As the investigation is concerned only with the coefficient at low gradients compared with that at higher gradients, the diminution in actual permeability did not vitiate the results except in so far as there was diminution during a test.

All the eight tests except the first were continued until the hydraulic gradient had diminished considerably below one foot to the mile. The computation of coefficients from the heads at successive observations gives somewhat irregular results in all tests, the irregularities increasing notably at heads below one foot to the mile and becoming excessive below about a half or a quarter of a foot to the mile. More even results are obtained if the computations are made for longer periods--for example, using the first and fourth observations, the second and fifth, etc. Obviously, the longer periods have greater change in head and therefore the errors in determining the head produce smaller irregularities; on the other hand, when the stage of the test is reached in which the gradient is very low the changes in head for any given period become much smaller, and consequently the errors in determining head produce

Table 1--Results of test 2

No.	Date	Time	Head	Hydraulic gradient	Period numbers	Coefficient of permeability
	1933	h m	mm	ft per mi		
1	Aug. 26	9 15	14.5	38.2		
2	28	9 15	8.6	22.7		
3	29	9 15	6.49	17.1		
4	30	9 15	4.69	12.4	1- 4	540
5	31	9 15	3.63	9.6	2- 5	549
6	Sep. 1	9 15	2.74	7.2	3- 6	549
7	2	8 45	2.12	5.6	4- 7	510
8	5	9 15	0.94	2.5	5- 8	515
9	6	9 15	0.63	1.7	6- 9	561
10	7	9 15	0.51	1.3	7-10	543
11	8	9 15	0.37	1.0	8-11	592
12	9	9 15	0.27	0.7	9-12	539
13	11	9 15	0.12	0.3	10-13	691
14	12	9 15	0.10	0.26	11-14	625
15	13	9 15	0.06	0.16	12-15	719

Table 2--Results of test 8

No.	Date	Time	Head	Hydraulic gradient	Period numbers	Coefficient of permeability
	1934	h m	mm	ft per mi		
1	Apr. 12	10 59	2.23	5.9		
2		13 16	2.06	5.4		
3		16 30	1.89	5.0		
4		19 33	1.65	4.4	1- 4	194
5		22 58	1.47	3.9	2- 5	191
6	13	8 55	1.03	2.7	3- 6	192
7		13 10	0.89	2.3	4- 7	193
8		16 00	0.81	2.1	5- 8	193
9		19 30	0.71	1.9	6- 9	201
10		23 45	0.617	1.6	7-10	190
11	14	8 41	0.449	1.2	8-11	195
12		12 45	0.362	0.95	9-12	211
13		16 56	0.326	0.86	10-13	204
14		20 41	0.280	0.74	11-14	216
					12-14	178
					13-14	223

large irregularities in the computed coefficients. The significant fact, however, is that there was no progressive change in the coefficient with diminishing gradient and that, according to the recorded water-levels, flow occurred at gradients as low as 0.05 foot to the mile.

In these tests a gradient of one foot to the mile was represented by a difference of water-level in the two reservoirs of about 0.40 millimeter. The cathetometer used gives essentially correct results for much smaller differences. Apparently the limitations of the apparatus are due to surface-tension effects in the glass pressure-tubes, as a result of which the water-levels in these tubes do not rise or fall continuously in immediate and complete response to changes in pressure but rather respond to the continuous pressure-changes with slightly intermittent movement. It appears that to get reliable results with still lower gradients it will be necessary either to use a more accurate method of measuring the differences in water-levels, or else to increase the length of the sample through which the water flows.

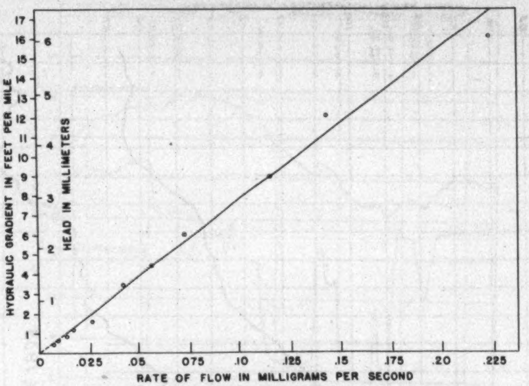


Fig. 2--Diagram showing results obtained in Test 2

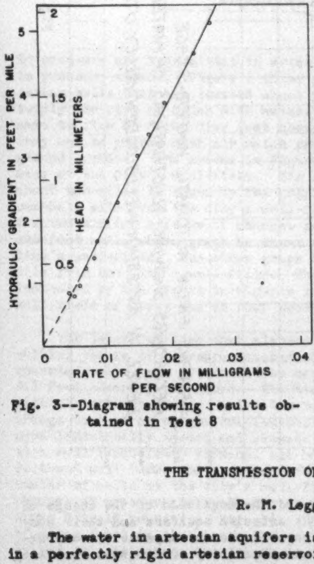


Fig. 3--Diagram showing results obtained in Test 8

The results obtained in tests 2 and 8 are shown in Tables 1 and 2 and in Figures 2 and 3.

Conclusions--The results obtained in this investigation indicate that for the type of sand used the flow varies at least approximately with the hydraulic gradient, down to a gradient of one foot to the mile and probably to considerably lower gradients. Moreover, they appear to afford evidence of some movement of water at gradients as low as one inch to the mile.

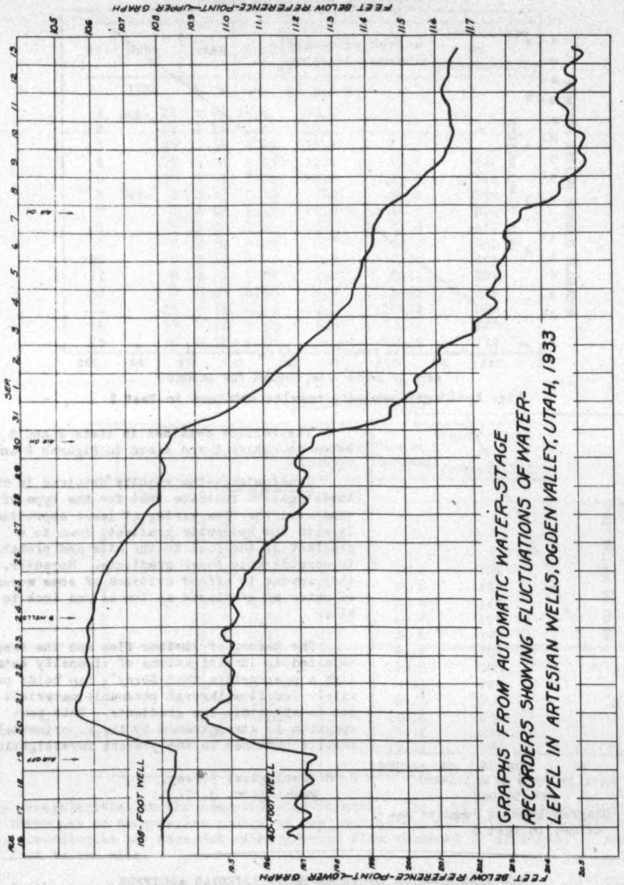
The theory of laminar flow and the results obtained in investigations of viscosity establish a presumption that Darcy's law holds precisely for flow through permeable materials under indefinitely low gradients. This presumption is strengthened by the experimental results obtained in the present investigation.

U. S. Geological Survey,
Washington, D. C.

THE TRANSMISSION OF PRESSURE IN ARTESIAN AQUIFERS

R. M. Leggette and G. H. Taylor

The water in artesian aquifers is confined under pressure. Under ideal conditions in a perfectly rigid artesian reservoir a change of pressure in one part of the reservoir should produce a corresponding change of pressure in all other parts of the reservoir. Theoretically, the transmission of pressure should take place rapidly and without any movement of water other than the small amount resulting from the compressibility of water. However, observations under natural conditions show that the transmission of pressure is not always rapid and that the rate of transmission appears to be

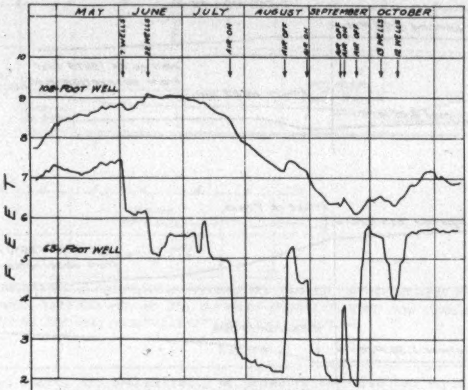


GRAPHS FROM AUTOMATIC WATER-STAGE RECORDERS SHOWING FLUCTUATIONS OF WATER-LEVEL IN ARTESIAN WELLS, OGDEN VALLEY, UTAH, 1933

Fig. 1

determined in great part by the distance traversed and the magnitude of the change of pressure. There are many reasons for believing that artesian aquifers and their confining beds are not perfectly rigid but that they are elastic and capable of compression and dilation (O. E. Meinzer, Compressibility and elasticity of artesian aquifers, Econ. Geol., v. 23, pp. 263-291, 1928). This appears to be the cause of the lack of rapidity of transmission of pressure in artesian aquifers.

During the course of ground-water investigations being conducted in Salt Lake and Ogden valleys, Utah, a number of tests were run to determine the rate at which changes



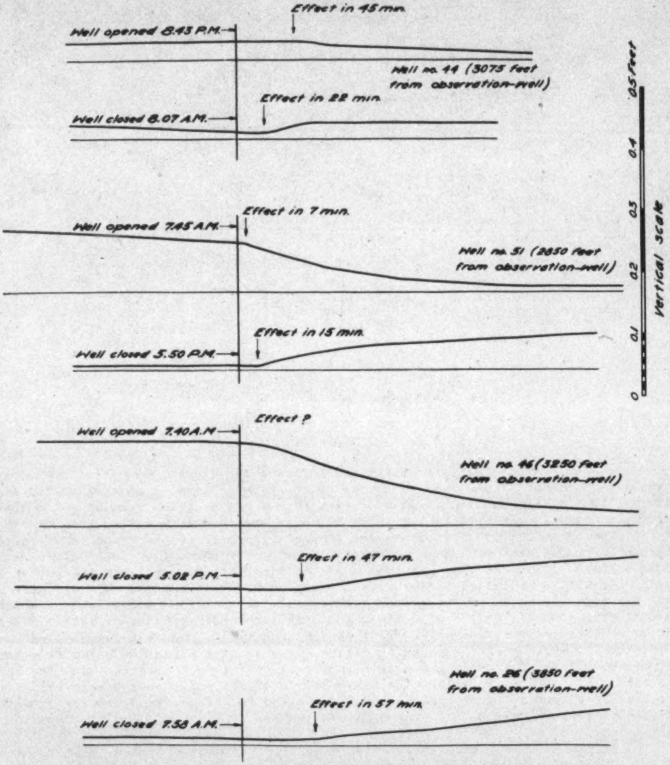
GRAPHS SHOWING WATER-LEVELS AT NOON EACH DAY IN ARTESIAN WELLS, OGDEN VALLEY, UTAH, 1933

Fig. 2

in pressure are transmitted in artesian aquifers and the distance to which such changes in pressure extend. Figure 1 shows graphs of the fluctuations of water-level in artesian wells that are located about two miles from a group of 50 artesian wells that supply the city of Ogden with water. The 50 wells are so arranged that they can be made to flow at about five feet above the ground surface or at the ground surface, or they can be pumped with air which produces a drawdown of about five feet below the ground surface. The arrows in Figure 1 show the times at which certain changes were made at the City's well-field. The effect produced by these changes at a distance of about two miles is shown by the graphs in Figure 1. Observation-wells located about one-half mile from the City's well-field show similar though greater effects. Figure 2 shows similar effects of changes in discharge from the City's well-field. The 108-foot well, whose graph is shown in Figure 2, is located about two miles from the City's well-field. The other graph in Figure 2 is from a well located about one-half mile from the City's well-field. The manipulation of the wells in the well-field, as indicated by the arrows in Figures 1 and 2, resulted in changes of discharge from the well-field of about one to four second-feet of water.

The length of time that elapsed after a well was closed or opened, before the resulting change of pressure reached observation-wells at various distances from the operated wells, was determined by means of a special recorder that had a time-scale of 0.1 foot covering two hours. The time-interval can be scaled from this recorder to within about two minutes and estimated to within about one minute. Figure 3 shows the change in head in an observation-well when four of the wells at the City's well-field were individually opened and closed. The opening of the well nearest to the observation well (2850 feet) affected the head in the observation-well in seven minutes. The farthest well (3850 feet), when closed, produced an effect in 57 minutes. When a number of wells at the City's well-field were manipulated, the time required for the changes of pressure to reach the observation-wells about two miles distant was from about 3 to 13 hours (see Fig. 1). The exact time cannot be told because fluctuations of water-level in the observation-wells due to changes in atmospheric pressure obscured to some extent the points at which the first effect was recorded.

In the Salt Lake Valley the artesian conditions appear to be much more complicated than those in the Ogden Valley. Conditions are further complicated because the discharges from a number of well-fields are connected to a distribution-system in which there is a back pressure. When the pressure in this distribution-system is changed,

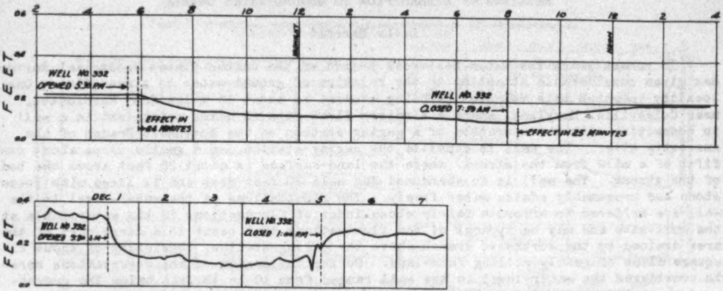


GRAPHS SHOWING CHANGE IN HEAD IN OBSERVATION-WELL WHEN DISTANT WELLS ARE OPENED OR CLOSED; OGDEN VALLEY, UTAH

Fig. 3

due to opening or closing wells connected to the system, the effect of the back pressure is transmitted to the aquifers through other wells connected to the distribution-system. A large number of tests were run in the Salt Lake Valley, and in general these tests showed the same results as were obtained in the Ogden Valley. Figure 4 shows the change in head in an observation-well resulting from the opening and closing of a well 0.8 mile distant. The maximum distance from a manipulated well at which a change in pressure was recorded in the Salt Lake Valley was 1.3 miles.

Observations in the Salt Lake Valley obtained by means of the special recorder described above showed considerable differences in the rate of transmission of pressure in artesian aquifers. In most cases where the manipulated well was near the observation-well, the transmission of pressure was so rapid that the time-interval could not be determined. In two tests where the manipulated well and the observation-well were



GRAPHS FROM AUTOMATIC WATER-STAGE RECORDERS SHOWING CHANGE IN HEAD IN ARTESIAN WELL NO. 73 WHEN ARTESIAN WELL NO. 332, 0.8 MILES DISTANT, IS OPENED AND CLOSED; FLOW OF WELL NO. 332 WAS 116 G.P.M.; SALT LAKE VALLEY, UTAH

Fig. 4

about 1600 feet apart, the transmission of pressure was also too rapid to be determined. In one case, 23 wells located about one mile from the observation-well were closed and the effect at the observation-well was recorded in five minutes. In another case, six wells located about a mile from the observation-well were opened and the effect was recorded in about 46 minutes. In the Salt Lake Valley the rate of transmission of pressure was generally higher when the manipulated wells were closed than when they were opened.

The head in a number of artesian wells ranging in depth from 70 to 218 feet was affected when wells of intermediate depth were opened or closed. All of these wells were cased to the bottom. This appears to have been caused by one of two methods of transmission of pressure: (1) If the confining beds are continuous rather than lenticular, the change of pressure in one aquifer may be transmitted to a higher or lower aquifer through the flexible confining beds; (2) if the confining beds are lenticular, the change of pressure in a well of one depth may be transmitted either around the end or through the flexible confining beds to a well of different depth. It is not known whether the confining beds in the Salt Lake Valley are continuous or lenticular.

It is apparent from the above that changes in pressure in artesian aquifers are transmitted over distances considerably greater than two miles. There are reasons for believing that, theoretically, changes in pressure in one part of an artesian reservoir should be transmitted all the way to the outcrop of the artesian aquifer. Obviously, a number of factors determine the rate at which a change of pressure is transmitted in an artesian aquifer. If a change of pressure is produced by changing the discharge of the manipulated wells by only a small amount, this change in pressure will not reach an observation-well at a given distance as rapidly as when the discharge from the manipulated wells is changed by a greater amount. Furthermore, if the depth of the manipulated wells is considerably different from the depth of the observation-well, the time required for the transmission of the change of pressure will be greater than if the manipulated wells and the observation-well are of the same depth. The rate of transmission of pressure is higher nearer the manipulated well than at greater distances from the manipulated well. In other words, the transmission of pressure decreases both in rate and magnitude as greater distances are reached.

U. S. Geological Survey,
    Washington, D. C.

RELATION OF STREAM-FLOW TO GROUND-WATER LEVELS

L. L. Harrold

In recent years the Water Resources Branch of the United States Geological Survey has given considerable attention to the relation of ground-water to stream-flow. One locality in which this relation is being studied is about 13 miles from Washington, near Colesville, Maryland, where a Kinnison float-gage is being maintained in a well in connection with the operation of a gaging-station on the Northwest Branch of the Anacostia River. The well is opposite the gaging-station, on a gentle slope about one-fifth of a mile from the stream, where the land-surface is about 20 feet above the bed of the stream. The well is an abandoned dug well 20 feet deep and is lined with loose stone and presumably admits water freely. The fluctuations of the water-level in the well are believed to afford a fairly close index of fluctuations in the water-table at the well-site and may be typical of the fluctuations that occur in a large part of the area drained by the Northwest Branch above the gaging-station, consisting of about 21 square miles of gently rolling farm-land. During the period of the observations herein considered the water-level in the well ranged from 10 to 16 feet below the ground-surface at the well and from 10 to 4 feet above the bed of the stream.

The Northwest Branch is entrenched an average depth of about 6 feet in a relatively flat valley from 400 to 800 feet wide. From the valley-floor the country rises gradually on both sides to altitudes of about 100 feet above it. In places the valley-floor is lower than the banks of the creek, has little or no surface-drainage, is somewhat marshy, and supports a growth of sedges and marsh and meadow-grasses. The banks of the creek and its larger tributaries are commonly bordered by a fringe of oak, poplar, sycamore, willows, and brush. The uplands and valley-slopes are well drained and contain little if any marshy land. They are wooded in places but for the most part have been cleared and are either cultivated or used for pasture.

Concurrent daily records of the stream-discharge and water-levels in the well have been made since May 1932, and the records for the period of 17 months to September 1933 have been critically studied. This period includes the greater part of the growing seasons in 1932, during which the rainfall was somewhat below average, and in 1933, during which the rainfall was materially above average.

Figure 1 shows: (a) The daily rainfall in inches at College Park, Maryland (about 8 miles from the gaging-station); (b) the daily gage-heights of water-surface in the well; and (c) a hydrograph of the daily discharge of the stream during periods when the stream is believed to have been fed wholly or almost wholly by ground-water.

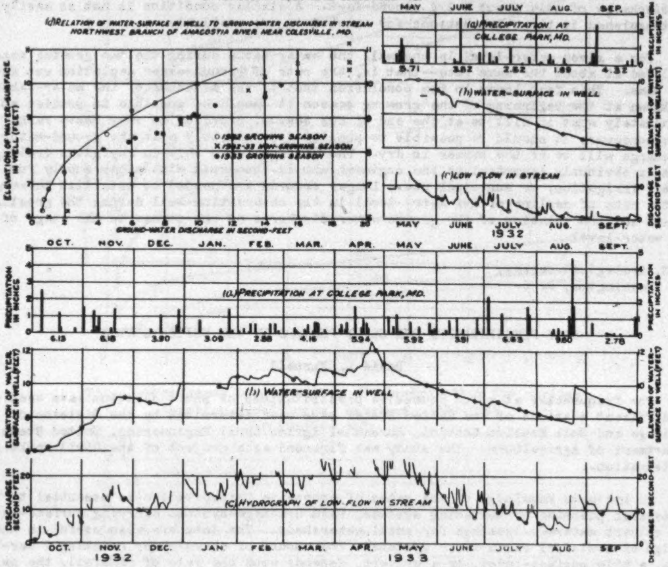
A study of the data that are graphically shown in Figure 1 leads to the following interesting conclusions:

During about four-fifths of the period of 17 months the stream was probably fed wholly or almost wholly by ground-water.

Light rains had no effect at any time on the water-level in the well. Moderately heavy to heavy rains had little or no effect during the growing season, but during the period of dormant vegetation such rains were followed by a sharp rise both of the water-level in the well and of the ground-water discharge of the stream, showing that there had been ground-water recharge. During the three months from May 1 to July 31, 1933, in which the rainfall amounted to 16.46 inches, both the ground-water level and the ground-water discharge of the stream declined persistently, whereas during the three months of dormant vegetation from October 1 to December 31, 1932, in which the rainfall amounted to 16.11 inches, there was a pronounced rise in the ground-water level and a corresponding increase in the ground-water discharge. However, a rain of 4.5 inches on August 23, 1933, recharged the ground-water to a great extent, thereby raising the water-table and increasing ground-water discharge.

The rise and fall in the ground-water discharge of the stream follows the rise and fall in the ground-water level with remarkable consistency. For weeks or even months at a time it would have been possible to make a close estimate of the discharge of the stream from the stage of the water in the well.

FIGURE 1 PRECIPITATION, WATER-SURFACE IN WELL, AND STREAM-FLOW AT NORTHWEST BRANCH OF ANACOSTIA RIVER NEAR COLESVILLE, MD.



The relation between the ground-water level and ground-water discharge, however, varies with the seasons and apparently with the rainfall during the growing season. This variation is brought out in a remarkable manner by plotting the discharge of the stream against the water-levels in the well for days when the stream was fed wholly from ground-water (see Fig. 1-d). Circles on Figures 1-b and 1-c show points used for plotting Figure 1-d. From this Figure it is apparent that for identical water-levels in the well the rate of ground-water discharge into the stream was comparatively small in the growing season of 1932 but much larger during the succeeding season of dormant vegetation and also during the growing season of 1933.

It is believed that the difference in the rate of ground-water discharge during the two growing seasons can be explained as follows: The abundant precipitation during the growing season of 1933 supplied most of the demands of the vegetation. In the growing season of 1932, however, the plants needed more water than was supplied by the scanty rainfall, and therefore they drew heavily on the ground-water, especially heavy drafts being made by the fringe of trees along the streams and by the marsh-grasses on the valley-flats. Therefore more of the underflow was intercepted in 1932 than in 1933. In 1932 the water-table beneath the flats, because of the greater draft by the grasses and smaller rainfall, presumably was lower than it was in 1933, and consequently the slope of the water-table and the rate of ground-water movement toward the creek were less. In the gradual decline of the water-level during the two growing seasons prior to the last of August, any given level was reached about a month later in 1933 than in 1932, and moreover the temperature from May to September averaged 1.°1 and 1.°6 above normal in 1932 and 1933, respectively.

During the growing season in 1932 there was a progressive change in the relation between the water-surface in the well and the ground-water discharge in the stream (Fig. 1-d). For a fall in the water-surface in the well from a stage of 10 to 9 feet, there was a decrease in ground-water discharge of about 4 second-feet; whereas for a fall in the water-surface in the well from a stage of 8 to 7 feet there was a decrease in discharge of only about 1-3/4 second-feet. A similar condition is not so easily distinguished in the other seasons for which data are available.

For a given water-level in the well the water-table during the two growing seasons declined at about the same rate--that is, the rate of ground-water depletion was about the same. This fact leads to the conclusion that if the altitude of the water-table is known at the beginning of the growing season it should be possible to predict approximately what it will be at the end of the season, provided no very heavy rains occur; moreover, it should be possible to predict approximately what the ground-water discharge will be if the summer is dry. The ability to do this in any given drainage-area is obviously important to the engineer who is concerned with water-supply for power, irrigation, or municipal use. Longer records are needed to establish thoroughly the rate of decline of the water-level in the observation-well during the growing season and the relation of the ground-water discharge of the stream to the stage of the water-level.

U. S. Geological Survey,
Washington, D. C.

HIGH PRECIPITATION FOR SHORT PERIODS IN THE UNITED STATES

David L. Yarnell

The frequencies at which excessive precipitations of short duration have occurred in different sections of the United States have been determined by the Division of Drainage and Soil Erosion Control, Bureau of Agricultural Engineering, United States Department of Agriculture. The study was financed as a project of the Civil Works Administration.

An intimate knowledge of the rates of excessive precipitation is essential to the successful planning of terracing systems, farm drainage-systems carrying surface-water, and culvert waterway-openings for small watersheds. The data are also useful in the design of municipal storm-sewer systems. The amount of storm-water reaching a terrace, a tile surface-inlet, or a culvert, depends upon the rate of rainfall, the period during which this intensity prevails, the percentage of rainfall that flows off, and the time of concentration of the watershed. The frequency with which certain rates of precipitation recur should be the foundation of intelligent design.

Available data relating to excessive precipitation at 206 of the United States Weather Bureau stations in the United States and two stations in its island possessions have been summarized and presented in the form of graphs. Formulas giving the maximum rates of precipitation for short periods of time up to 400 minutes have been derived, and the frequency of occurrence of such storms is shown. In all, 28,077 different rain-storms were studied.

Since storms of great intensity generally extend over small areas, it is believed that this study is sufficiently comprehensive to enable one to predict with reasonable accuracy the probable frequency of a storm of any given rate in any portion of the United States.

Two charts have been prepared for each station, one giving the frequency of high precipitation-rates and the other showing the duration of precipitations of high intensity. Samples of these curves are shown in Figures 1 and 2. Figure 1 shows the maximum rate for a certain duration which may be expected at any interval. Figure 2 shows the excessive rates which actually occurred in the period of record, without regard to frequency of occurrence.

Intensity-charts have been compiled for the entire United States from the frequency-duration curves for the individual stations. For 5-, 10-, and 20-year frequencies, intensity charts for 5-, 10-, 15-, 30-, 60-, and 100-minute durations were compiled. One of these diagrams, showing the intensities for ten-year frequency, ten-minute-duration precipitations, is given in Figure 3. These intensity-charts or

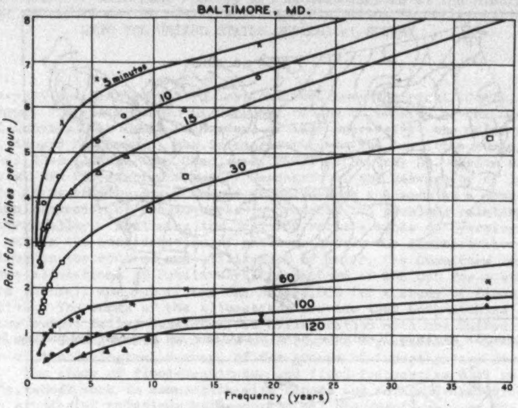


Fig. 1--Frequency of occurrence of precipitation for various durations, Baltimore, Maryland, 1896-1933

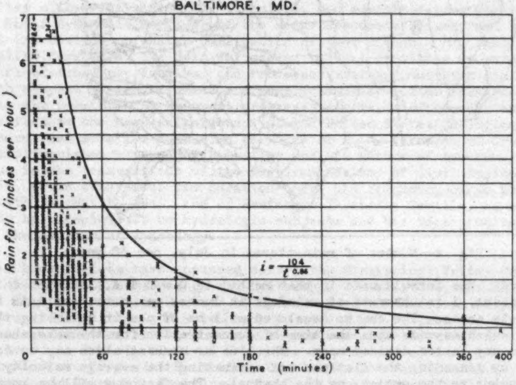


Fig. 2--Excessive precipitations, Baltimore, Maryland. 1896-1933

iso-pluvials are interesting in that they show the variation in rainfall-intensity throughout the entire United States.

The amount of surface-runoff from a heavy rainfall, and the damage caused through floods or soil-erosion in any locality often depend in considerable measure upon the time of the year when the storm occurs. The number of excessive storms that have occurred in each month, adjusted to a period of 30 years, was determined, one drawing for each month. The chart for July is shown in Figure 4. Comparison of these charts for the various months will show in what months heavy rain-storms are most frequent for any part of the United States.

The results of these studies are extremely useful in computing runoff by the

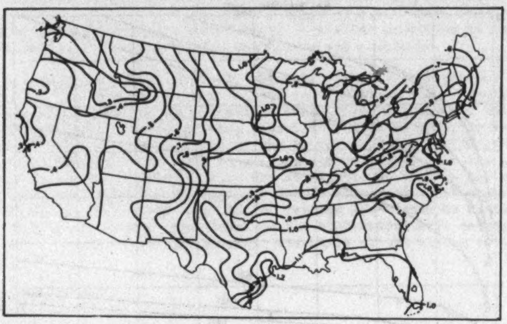


Fig. 3--Amounts maximum 10-minute precipitations of 10-year frequency in inches

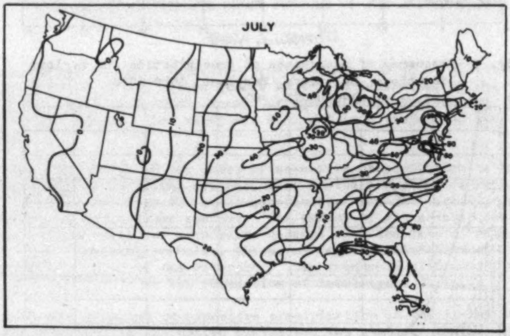


Fig. 4--Number of rain-storms in July, per 30 years

rational method. The formula used in that method is Q = C I A, in which C is the runoff coefficient, I is the rate of rainfall in inches per hour, and A is the area of the watershed in acres. The charts developed will be of use in selecting the value of the factor I, which depends upon the time of concentration for the watershed, and also upon the frequency-period decided upon. The time of concentration may be determined approximately by measuring the distance and estimating the average velocity from the most distant point to the outlet, by the channel. The factor A will be known for any specific case. Values of C for small agricultural areas have been given by C. E. Ramser (Runoff from small agricultural areas, J. Agri. Res., v. 34, pp. 797-823, U. S. Dep. Agri., 1927), and for impervious areas are stated in many text-books on sewer-design.

Bureau of Agricultural Engineering,
U. S. Department of Agriculture,
Washington, D. C.

STATUS OF STUDY OF RAINFALL, RUNOFF, AND RELATED FACTORS BY THE MISSISSIPPI VALLEY COMMITTEE OF THE PUBLIC WORKS ADMINISTRATION IN COLLABORATION WITH THE UNITED STATES GEOLOGICAL SURVEY

W. G. Hoyt

The members of the Mississippi Valley Committee are: Morris L. Cooke, of Philadelphia, chairman; Professor Harlan H. Barrows, of the University of Chicago; Herbert S. Crocker, of Denver; Dean Henry S. Graves, of Yale University; the Chief of Engineers, General Edward M. Markham, who is represented on the Committee during his absence by Colonel Glen E. Edgerton; Charles H. Paul, of Dayton; Dr. Harlow S. Person, of New York City; and Professor Sherman M. Woodward, of the University of Iowa. The Committee meets in Washington every second or third week and acts as a consulting board to the Administrator of Public Works on projects and problems relating to the Mississippi River Valley. Realizing the need for various kinds of hydrologic information for use in the consideration of problems before the Administrator, especially those involved in the control and utilization of water, the Committee recommended and obtained two allocations of Public Works funds--one of $25,000 for a study of relations between rainfall and runoff and one of $20,000 for a study of floods and flood-frequencies. The terms of the allocations provide that both studies shall be made by the Mississippi Valley Committee, in collaboration with the United States Geological Survey. Arrangements have been made for the organization, in the Water Resources Branch of the Geological Survey, of two groups of investigators for making these studies. The study of flood-magnitudes and flood-frequencies will be directed by C. S. Jarvis, whose work in connection with floods and rainfall-analysis is well known, and the studies of relations between rainfall and runoff will be directed by the author.

Both studies will receive general, technical, and administrative supervision by N. C. Grover, Chief Hydraulic Engineer of the Water Resources Branch, and R. W. Davenport, Chief of the Division of Water Utilization of that Branch. Mr. Paul, of the Mississippi Valley Committee, has been designated by that Committee to maintain contact with the flood-frequency studies, and Professor Woodward has been similarly designated with respect to the rainfall and runoff studies. Close relation will be maintained with the Committee by frequent progress-reports, conferences, and discussions. In addition to the regular personnel of the United States Geological Survey, arrangements have been made for part-time services of M. M. Bernard, of Crowley, Louisiana, a distinguished student of hydrology and the author of numerous articles and discussions in the transactions of the American Society of Civil Engineers, of H. Alden Foster, whose studies of the duration-curve and frequency-curve have made him an authority with respect to them, and of Professor Thorndike Saville, of New York University, who has specialized on hydrologic subjects and has been prominent in the activities of the Section of Hydrology.

Many noted hydrologists have appeared before the Mississippi Valley Committee and discussed questions of meteorology and hydrology. In addition, the American Society of Civil Engineers and the Section of Hydrology of the American Geophysical Union have appointed committees of seven each to advise and collaborate with the Mississippi Valley Committee in connection with the contemplated studies. The Committee of the American Society of Civil Engineers is composed of Gerard H. Matthes, chairman, Ivan E. Houk, Frederick H. Fowler, Charles W. Sherman, Daniel C. Walser, Robert E. Horton, and George R. Spalding. The Committee representing the Section of Hydrology is composed of W. W. Horner, J. A. Harman, A. F. Meyer, Professor G. W. Pickels, L. K. Sherman, Roy Towl, and J. W. Woermann.

It is apparent that many outstanding students of hydrologic problems will be associated with the Mississippi Valley Committee. Mr. Jarvis will outline the status of the flood-frequency studies. It is contemplated that the study of relations between rainfall and runoff will be conducted in full coordination with the flood-frequency studies but along somewhat different lines. Over broad areas little is now known of the relations between the so-called "direct surface-runoff" and the flow derived from ground-water discharge. In large measure the ground-water flow represents the useful or usable portion of the stream-flow, whereas the direct surface-runoff that occurs at high stages is largely destructive unless controlled or regulated. It is planned to study the relations between precipitation, temperature, evaporation, transpiration, direct surface-runoff, ground-water runoff, and infiltration as a basis for determining variations in soil-moisture and ground-water conditions. In addition, studies will be made of the relations between storm-precipitation, snow, temperature, and direct surface-runoff.

So far as possible, it is planned to undertake studies that will be of immediate value to the Mississippi Valley Committee in connection with the projects for regulating and controlling direct surface-runoff in the Mississippi River Valley. In addition, the studies will form a logical extension of past hydrologic studies. The studies as outlined may be confidently expected to yield results whose value will be commensurate with their cost. The United States Geological Survey will be glad to receive suggestions from members of the Section of Hydrology who are interested in these subjects and especially to be advised of any studies that may have been previously made in the Mississippi Basin or elsewhere along the lines of the proposed investigations.

U. S. Geological Survey,
Washington, D. C., April 23, 1934

STATUS OF STUDY OF THE FREQUENCY AND MAGNITUDE OF FLOODS BY THE MISSISSIPPI VALLEY COMMITTEE OF THE PUBLIC WORKS ADMINISTRATION IN COLLABORATION WITH THE UNITED STATES GEOLOGICAL SURVEY

C. S. Jarvis

Active work under the recently authorized project relating to floods and their frequencies began in March, and such progress as may be reported at this time is largely that of organization and preliminary planning.

One of the outstanding and impressive features of the organization is the provision for cooperative effort, whereby the mature judgment and possibly diverse viewpoints of various committees and consultants may be utilized to the fullest advantage. This arrangement should provide the necessary safeguard against adoption of immature individual views or favorite methods of analysis, to the exclusion of others of equal or greater merit. On the other hand, it is conceivable that too much of the limited time might be consumed in preliminary discussions of basic principles, methods of analysis, and formulas dealing with either magnitude or frequency of floods, if unanimity of opinion among several professional groups must precede the main work under the project authorized. In effect, such a procedure would require a practical and workable solution before the basic data had become available. To avoid such delays, a definite line of procedure has been proposed for consideration.

The first requirement seems to be an understanding of what data should be assembled in preparation for analysis. This has called for a brief survey of all methods thus far proposed for dealing with flood-frequencies or flood-magnitudes and found to have a semblance of reliable basis. Examination and comparison of formulas and methods of analyzing flood-frequencies are now well under way, so that it has been possible to prepare tentative forms for the recording of pertinent information.

It is now proposed to list, tabulate, and summarize representative flood-records, with all significant data that may be required by any of the most prominent methods of analysis. Concurrently, the various procedures dealing with problems of flood-frequencies and magnitudes may be examined, and each in turn applied to certain representative long records. This process should establish a basis for comparing the adaptability of the various methods, while affording the maximum practicable opportunity for the application to these flood-records of anyone's favorite formula or method of analysis.

The increased activity in the field of stream-gaging incidental to the recent series of river-surveys and reports, under House Document 308, 69th Congress, 1st session--usually called the "308 reports"--resulted in establishment of about 600 gaging-stations by the United States Geological Survey. While the "308 surveys" may account for only five or six years of record and many of the 600 gaging-stations have been discontinued, even those short records have proved of incalculable value in connection with new or current problems. They prompt the expression of a hope that never again may important stream-gaging stations be abandoned because of lack of funds and appreciation.

It should be borne in mind that a constantly accumulating mass of hydrographic and hydrologic data is now available, awaiting condensation, arrangement, classification, comparison, and coordination for practical use. Furthermore, the various Statewide investigations and the studies including large drainage-basins in several States have brought forward important contributions to the profession, but the nation-wide field now beckons, or challenges, according to one's viewpoint. There seems to be no disposition to forecast results of this study; but if the possibilities of this investigation are fully realized, it should prove to be a profitable investment. The real problem is how to utilize the time and facilities so as to give maximum returns; and the evident answer is in painstaking, methodical work, under proper direction and with timely constructive criticism, consultation, and control.

U. S. Geological Survey,
Washington, D. C., April 25, 1934

EFFECTS OF ICE ON THE FLOW OF THE UPPER MISSISSIPPI RIVER

A. H. Frazier

During the past winter the engineers of the St. Paul district of the United States Geological Survey had the opportunity of making a detailed study of ice-conditions on the upper Mississippi River at the gaging-stations at Prescott, Wisconsin, and Winona, Minnesota, 30 and 116 miles respectively downstream from St. Paul. In the course of this study two facts of general interest were ascertained. It was found that during the frozen period the discharge at both stations fluctuated in remarkable unison with the fluctuations of temperature, and that the natural reservoirs, Lake St. Croix and Lake Pepin, helped to produce these fluctuations.

The relation between the discharge and temperature was not at first apparent at both stations. At Winona the stage fluctuated with the temperature, but at Prescott the stage was not appreciably affected by the temperature. However, after numerous measurements were made, it became apparent that the discharge fluctuated with the temperature at both stations, regardless of the change or lack of change in stage, and that the reaches where the River remained open all winter were the points where the discharge-fluctuations originated.

The Prescott Gage is immediately below the point where Lake St. Croix discharges into the Mississippi (see Pl. 1). Four miles upstream on the Mississippi is the navigation dam at Hastings, Minnesota. This dam is operated in such a manner as to maintain a uniform stage in the pool, and it is therefore believed that approximately the natural flow of the Mississippi passes through the gates. This arrangement causes the following conditions to affect the flow of the Mississippi River past the Prescott Gage:

(1) The River remains practically free from surface-ice the entire winter from the Hastings dam to a point more than a mile below the gage. Incidentally, all the discharge-measurements at Prescott were made in this open stretch of water, and so their accuracy is as good as that of measurements made at any other time of the year.

(2) Frazil ice forms in large quantities in this reach of open water during cold spells. The frazil floats on the surface until it arrives at the place where the River has a complete ice-cover. There it is drawn beneath the surface-ice and travels downstream until it becomes lodged at some constriction in the channel. Once having lodged, it acts like a sieve to accumulate other particles, and this process continues until a jam is formed. Plate 1 shows the conditions.

(3) Jams due to frazil ice at this station are apparently dissipated only by a rise in temperature. Normally, a river accommodates itself to such jams in one or more of the following ways: (a) The river rises behind the jam until a sufficient head is created to push the obstruction downstream or until the amount of water that is forced through the jam is equal to that which approaches it. At Prescott neither

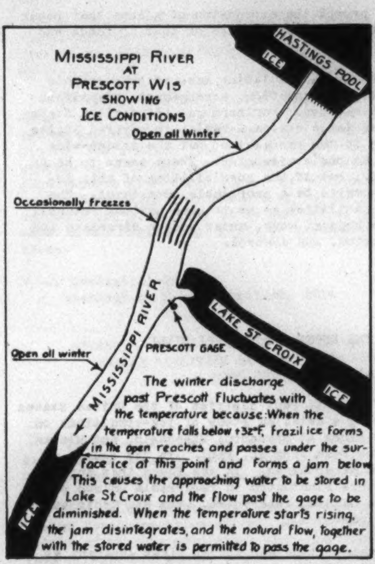

MISSISSIPPI RIVER
AT
PRESCOTT WIS
SHOWING
ICE CONDITIONS
HASTINGS POOL
ICE
Open all Winter
Occasionally freezes
MISSISSIPPI RIVER
LAKE ST CROIX
PRESCOTT GAGE
Open all winter
ICE
ICE
The winter discharge past Prescott fluctuates with the temperature because: When the temperature falls below +32°F, Frazil ice forms in the open reaches and passes under the surface ice at this point and forms a jam below. This causes the approaching water to be stored in Lake St. Croix and the flow past the gage to be diminished. When the temperature starts rising, the jam disintegrates, and the natural flow, together with the stored water is permitted to pass the gage.

Plate 1

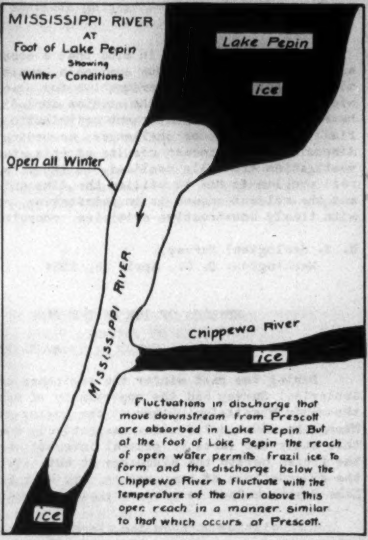

MISSISSIPPI RIVER
AT
Foot of Lake Pepin
Showing
Winter Conditions
Lake Pepin
ice
Open all Winter
MISSISSIPPI RIVER
Chippewa River
ice
ice
Fluctuations in discharge that move downstream from Prescott are absorbed in Lake Pepin. But at the foot of Lake Pepin the reach of open water permits frazil ice to form and the discharge below the Chippewa River to fluctuate with the temperature of the air above this open reach in a manner similar to that which occurs at Prescott.

Plate 4

of these occurred because any rapid rise in stage was absorbed by storage in Lake St. Croix. (b) The river freezes completely over, preventing the formation of additional frazil. When such a jam is not reinforced by additional material, it soon melts or passes downstream. This did not happen at Prescott, because the temperature did not stay cold long enough to freeze the entire surface of the river. (c) The temperature rises, with the result that additional supplies of frazil are cut off, and the jam disintegrates. This apparently happened at Prescott.

(4) The discharge of the Mississippi past Prescott fluctuates with the temperature. When the temperature drops, a frazil jam forms below Prescott and obstructs the passage of water down the main channel, causing a large part of the water approaching from upstream to be stored in Lake St. Croix. When the temperature rises, the frazil jam disintegrates, and the discharge is increased to the normal flow plus that which had been stored in the lake.

It might be well to note at this point the part played by Lake St. Croix. In this latitude at the outlet of a lake or where two large rivers unite, the channel immediately below remains free from ice the entire winter. In this manner Lake St. Croix contributed to keep the main channel open and make conditions ideal for the formation of frazil ice. As a result of its large storage-capacity, the Lake kept the stages at Prescott fairly uniform, while the discharge below Prescott fluctuated rapidly. Because the Lake prevented the stage from rising rapidly, the frazil jams were not packed as tightly as they would have been if a head of water had been built up behind them. As the jams were loosely packed, they disintegrated more readily when the temperature rose. Finally, the water stored in the Lake during a period of falling temperature was released during a period of rising temperature. This characteristic of a natural reservoir helping to create fluctuations in the main stream during the winter is in marked contrast to its propensity to smooth out fluctuations by means of its storage-capacity during the summer. Plate 2 shows the uniformity of the discharge during the summer and the irregularity during the winter.

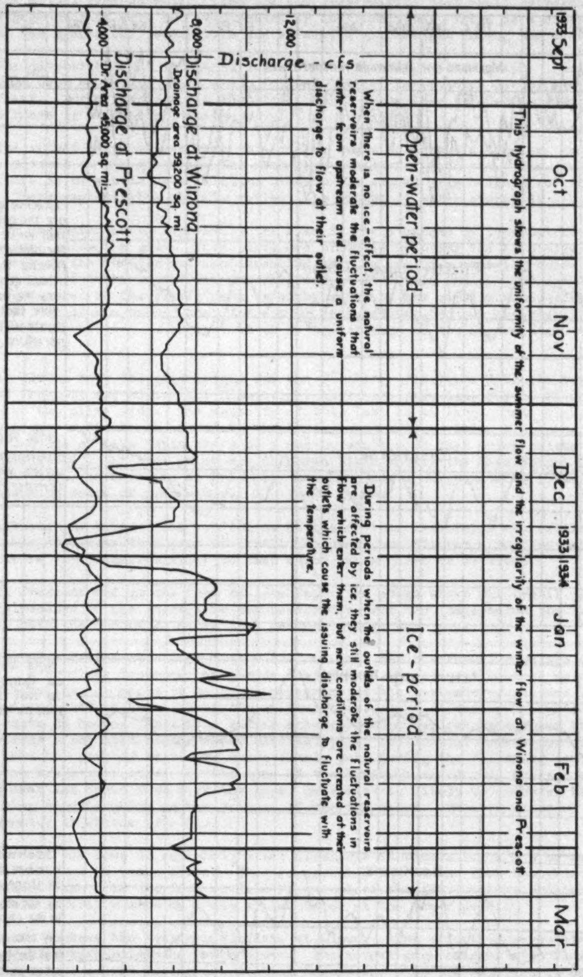
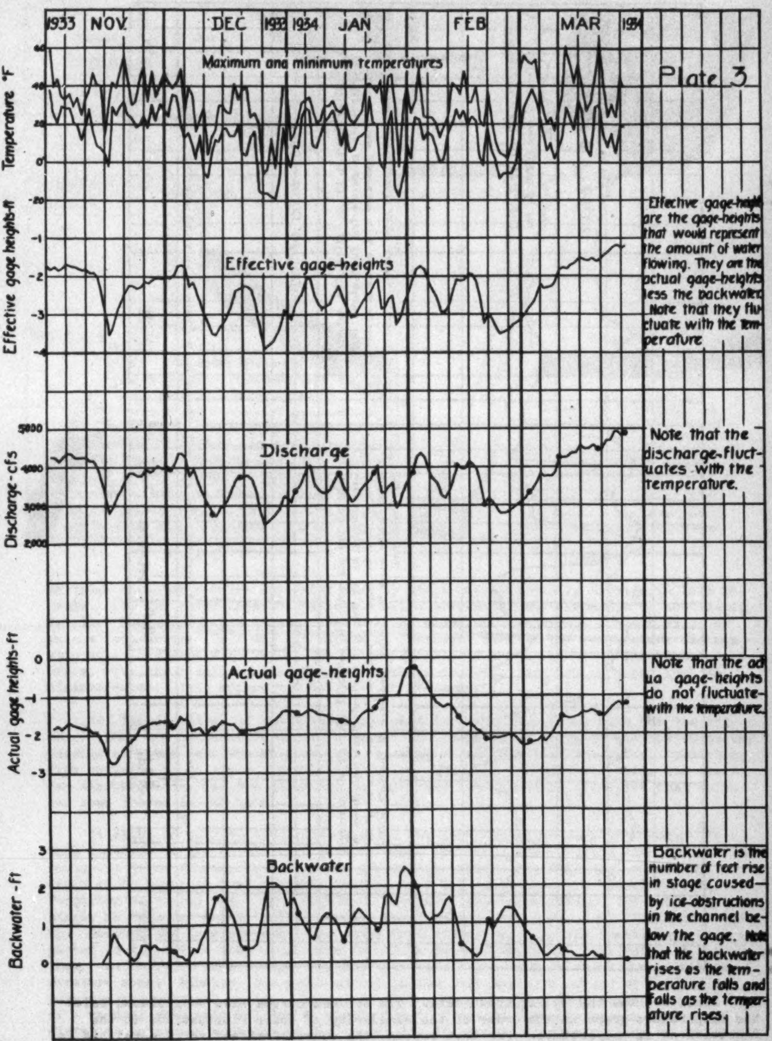


Plate 2

Plate 3 shows the hydrographic data. The several curves have been placed below the temperature-graph in the order of the similarity of their fluctuations to the fluctuations in temperature. For that reason, the curve of effective gage-heights is placed first. The effective gage-heights are obtained by subtracting the backwater



Effective gage-heights are the gage-heights that would represent the amount of water flowing. They are the actual gage-heights less the backwater. Note that they fluctuate with the temperature

Note that the discharge-fluctuates with the temperature.

Note that the actual gage-heights do not fluctuate with the temperature.

Backwater is the number of feet rise in stage caused by ice-obstructions in the channel below the gage. Note that the backwater rises as the temperature falls and falls as the temperature rises.

Plate 3--Mississippi River at Prescott, Wisconsin, 1933-34

from the actual gage-heights. They are the gage-heights that would represent the flow if the gage-heights were not complicated by ice-formation. There is a close agreement between the graphs for temperature and effective gage-height during the winter period.

The discharge-graph is placed second below the temperature-graph. For reasons that have been explained, this graph follows that of temperature during the period of ice-effect. During the periods when the channel below Lake St. Croix is not affected by ice there is no apparent similarity.

The actual gage-heights were obtained by means of a recording gage, and the points plotted on the graph are the mean gage-height for each day. The graph shows that there is no appreciable relation between the actual gage-heights and the temperature. These gage-heights chiefly reflect the amount of water stored in Lake St. Croix.

The backwater-curve represents the rise in stage caused by ice-obstructions in the channel below the gate. This curve was produced by using the discharge-measurements made at the station and supplementing them by use of a capacity-curve of Lake St. Croix and power-house records at St. Paul and at St. Croix Falls. The decrease in discharge caused by the frazil jams is compensated by the simultaneous increase in backwater, in such a manner that the actual gage-heights did not materially change. This unusual condition is brought about by the storage of the approaching water in Lake St. Croix.

At Winona both the gage-height and the discharge fluctuate with the temperature. Between Prescott and Winona the Mississippi widens to form Lake Pepin, 22 miles long and about two miles wide. The capacity of this Lake is so large that it absorbs the fluctuations in discharge caused by the frazil obstructions below Prescott. At the downstream end of Lake Pepin there is a set-up similar to that which exists at Prescott (see Pl. 4). At this point the Chippewa River enters the Mississippi from the Wisconsin side, so here, as at Prescott, there exists a large natural reservoir and a corresponding reach of open water.

Although no data on the conditions at the foot of Lake Pepin are available, it is reasonable to assume that jams of frazil ice cause the discharge to fluctuate with the temperature in a manner similar to that which takes place at Prescott.

At Prescott and at the foot of Lake Pepin the stage above the frazil jams remains uniform because of the storage in the reservoirs, but the stage below the ice-jams changes with the amount of water that passes through the jams.

The fluctuating discharge at the foot of Lake Pepin eventually passes the gage at Winona. A complete ice-cover at Winona complicated the stage-discharge relation at the station, but by means of numerous measurements the backwater-curve was defined. It was found that at the time of the initial freeze-up 4.8 feet of backwater was created within 24 hours. This is a rather extreme though typical example of the backwater that occurs along most of the upper Mississippi at the initial freeze-up. It was found that the peak of backwater wears slowly away during the following months until the first break-up occurs. At the time of the break-up and during the succeeding period when ice cakes flow past the gage, backwater is likely to occur at this station in varying amounts owing to the jamming of the ice cakes. This is shown on the curve of backwater at Winona (Pl. 5).

The extreme lows in gage-height and discharge at Winona lag a day or two behind the extreme lows in temperature. This is probably due to the fact that Winona lies 38 miles downstream from the foot of Lake Pepin, where the fluctuations originate, and they would naturally show up a day or two later at the lower point.

Plate 5 shows the hydrographic data at Winona. The effective gage-heights and discharge fluctuate with the temperature. The actual gage-heights also fluctuate with the temperature except during the initial freeze-up, when the relation is complicated by the ice effect below the gage. The backwater-curve shows that an ice-obstruction formed below the gage at the time of the initial freeze-up and that it gradually wore away until the break-up occurred. At the time of the break-up several ice-jams formed below the gage, and a few peaks of backwater resulted from these jams.

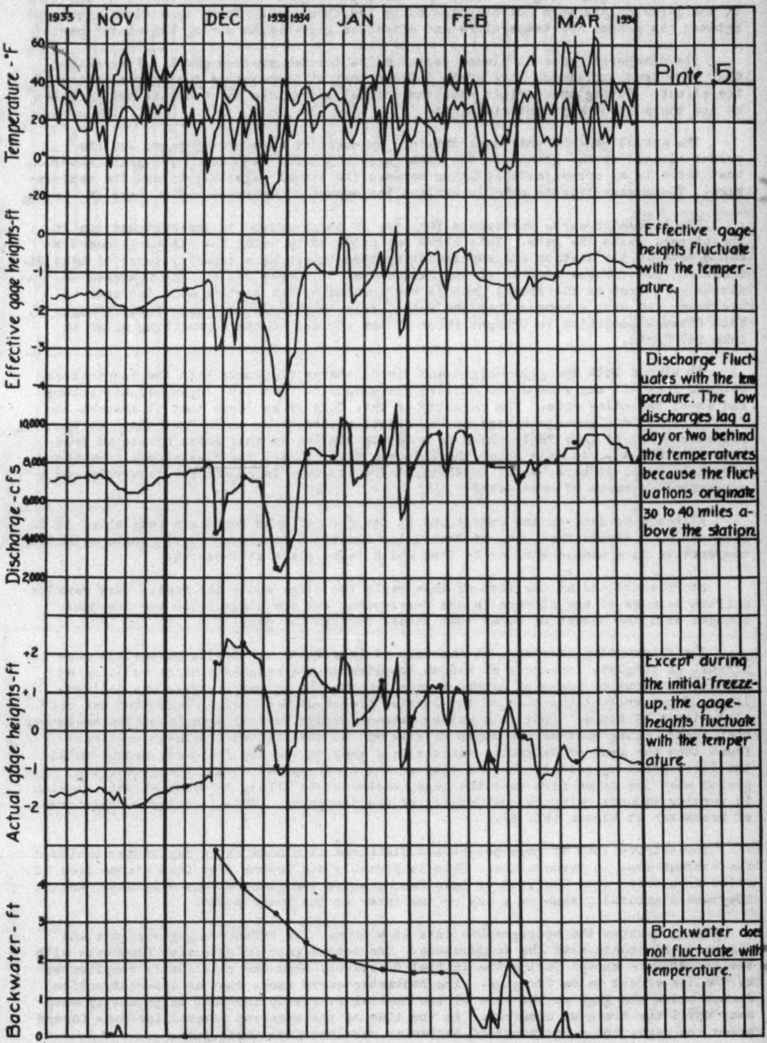


Plate 5

Effective gage-heights fluctuate with the temperature.

Discharge fluctuates with the temperature. The low discharges lag a day or two behind the temperatures because the fluctuations originate 30 to 40 miles above the station.

Except during the initial freeze-up, the gage-heights fluctuate with the temperature.

Backwater does not fluctuate with temperature.

Plate 5--Mississippi River at Winona, Minnesota, 1933-34

Some of the practical benefits of this study, from the hydrographer's viewpoint, are as follows:

The daily discharge at either of these stations can not be obtained with even reasonable accuracy by using the records at one station and adjusting them by a coefficient to obtain the discharge at the other. Plate 2 shows that during a period in December the discharge was less at the downstream station than at the upper station. In the case of the monthly mean discharges, a more reasonable relationship exists between the two stations.

On account of its smooth backwater-curve, a reliable record can be obtained at Winona by getting one measurement to define the first peak of backwater and following it by a measurement once a month until the break-up occurs. During the break-up period frequent measurements are desirable, if it is possible to obtain them.

At Prescott frequent measurements during the entire winter are necessary to define the erratic backwater-curve, but if measurements cannot be made, this study provides justification for assuming that the discharge fluctuates with the temperature.

At other stations on the Mississippi a study should be made to see how local conditions compare with those of Prescott and Winona, bearing in mind that a combination of the two might easily exist or that some entirely different local conditions might exert the dominating influence. If winter records are to be obtained for several years at a station, the first year would probably be the best time to make an intensive study such as this, because it might show where economies can be effected or whether the station would be too expensive to operate in the manner necessary to get the desired accuracy.

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FLOODS AND THEIR ECONOMIC IMPORTANCE

Gerard H. Matthes

Floods perform tasks of fundamental importance in Nature's household, tasks which no other agency can perform. Of first importance in this respect is the periodic removal by flood-waters of the debris accumulations which form in stream-channels, and which, if not removed, cause channel-deterioration. In any undisturbed watershed there is a sensitive natural balance between soil-erosion, runoff, and the debris-carrying capacity of streams. Any change wrought in either of the first two invariably affects the third.

Next to transporting debris, flood-waters, through their overflow and through deposition of their finer silt-burden, create alluvial lands of great fertility, and by the same process maintain this fertility. The value of this has been recognized and utilized extensively by the ancients, and by our early settlers. Strange as it may seem, this rich heritage appears to be no longer appreciated as it once was. The modern farmer's desire is to keep flood-water off his land by means of levees or storage-reservoirs. Although this causes his soil to become impoverished and at the same time requires him to pay construction and maintenance assessments and even buy fertilizer, still he prays for flood-control. The economic aspects of this situation will not be discussed here. Other important services which only floods can render are the rebuilding of banks of meandering streams and the building of delta lands. Destructive and undesirable as floods may appear to man from his customary viewpoint, there is no side-stepping the fact that floods are also creative and beneficial.

What then are the consequences of river-control if carried beyond sane limits? The object of this discussion is to emphasize that there is a definite limit beyond which flow-regulation must not be carried lest serious damage befall future generations. Also, that such regulation, if properly planned, need not interfere with debris removal from stream-beds. The basic principle involved is that any living stream, viewed as a carrier of debris, operates at greatest efficiency when flowing bank-full or nearly bank-full, and that therefore bank-full discharge, at suitable intervals, if made an essential feature in any river-development program, will preserve the physiographic balance.

A river and its tributaries may be likened to a gigantic sewer-system, ever receiving the wastes, both mineral and organic, from large areas--wastes that are not transported by it as fast as received and which, if not removed at intervals, cause clogging. To so regulate the flow of a river, through storage, as to give it a year-round uniform discharge, assuming that this much-cherished idea is practicable, would be on a par with building a sewer-system without making provision for flushing it. What the intermittent discharge from an automatic flushtank does for a sewer, flood-discharge does for a stream.

What constitutes the debris burden of natural streams; what causes it to accumulate in stream-channels; why are bank-full discharges required to move it? These questions of stream-dynamics are too well known to require reexamination here; but certain phases of these questions are rarely given the attention that is due them, and these will be discussed. First to be considered is the resistance to removal offered by sedimentary deposits that have become compacted.

Some degree of compaction affects all deposits that have lain undisturbed under water whether in the form of detached bars at cross-overs, point-bars building out at convex shore-lines, general filling in of large areas of relatively flat river-bed as for instance in the bottoms of pools during low water, or debris fans formed at the mouths of tributaries. Compaction means that ordinary tractive-force values such as brought the bed-load materials to their resting place, are not able to set these same materials in motion again, but that either greatly increased tractive force, such as only very high stages can produce, or else energy-forms of an entirely different sort, are required to accomplish removal. If it were not for compaction, all sedimentary materials dropped on a stream-bed would be picked up and carried downstream again with the first appreciable rise in stage. Actually, a rise in stage creates only enough additional tractive force to move the mobile materials lying on the bed. Those that have become compacted offer decided resistance to traction. The finer materials, such as silts and clays, cohere more firmly than do the coarser sands and gravels. Hence arises the anomaly that the materials which are most readily transported by water, usually in suspension, are those which offer the greatest resistance to movement after they have assumed the form of compacted deposits.

Compaction results from several causes acting either jointly or independently. Besides the puddling action of water, which tends to arrange individual grains into a mechanical bond by packing the interstices between the coarser particles with finer ones, and the pressure exerted by superimposed materials plus the weight of water, two other agencies are especially active as consolidators of sedimentary debris. These are colloids and organic matter. Both have adhesive properties. The former are present in most river-water in the form of colloidal clays which move in suspension. Organic matter is as much a part of soil-eroded debris as is mineral matter. In addition, all living streams are prolific mediums for the creation of animal and vegetable forms of life. The intrusion of such organic matter into any quiescent sedimentary materials in the forms of bars, bed, or banks submerged for any length of time in either fresh or salt water, takes place with astonishing rapidity during the summer and fall, and less so at other times. As the summer and fall are, in most localities, the low-water season, when little sedimentary load moves, it will be clear that climatic conditions are a material contributing factor in this phase of compaction. Whatever the various forms of organic intrusion may be, they serve to coat sand and silt-grains with a slime that promotes coherence and the formation of crusts. The latter teem with bacterial, animal, and vegetable life.

Superficial eye-observations of these processes are not readily made in turbid streams, but are not difficult to make in the clear waters at the seashore and in tidal basins. Outdoor laboratory models, which have been permitted to lie idle for a few days in warm weather become veritable breeding grounds for a great variety of organisms, and these convert the movable bed-materials into crusts. Irrigation-canals afford excellent illustrations of the compaction of sediments. Designed, as a rule, to carry only fine materials in suspension, the flow in such canals and ditches is rarely able to pick up these fine materials once they have settled out and become compacted. In unlined irrigation-ditches, sediment removal by flushing is impracticable as slopes and cross-sections are designed to prevent scour of beds and banks. Hence, periodic cleaning out by hand labor or by excavating machinery must be resorted to in order to maintain channel-capacity.

By contrast, natural channels, which have not been tampered with by man, do maintain their normal carrying-capacity through the instrumentality of high stages. And this is true of the largest rivers as well as of the smallest headwater rivulets; it is true of tidal estuaries as well as of the arroyos of the arid west, of the sand-choked rivers of the Great Plains, and of the bayous of Louisiana. The manner in which this principle operates is different in each individual stream and no one rule applies to all. Rainfall, soil, vegetation, and topography are the main controlling factors, and the endless number of combinations that result from them are found reflected in the great variation in characteristics of the physiographic balance as found in different watersheds. Space does not permit of alluding to more than a few outstanding types.

Rivers flowing in channels carved in the living rock are capable of removing, in a single great flood, bars and even islands covered with trees that may have been forming in them over a period of years and have become thoroughly compacted. The writer has had occasion to witness such occurrences in the Susquehanna River where its bed and banks consist of granitic rock. Floods in this river may occur at any time of the year. The lesser floods, though frequent, are not capable of removing the major debris accumulations but often operate to increase the size of the latter. It requires flood-flow of at least bank-full proportions to scour these away.

In alluvial streams, beds and banks consist of erodible materials. When compacted debris accumulations do not yield readily to scour, the banks are made to recede through sliding and caving, and the channel regains normal carrying-capacity, for both water and debris, by shifting. A meandering stream may well be defined as one that is forever detouring around the sedimentary deposits of its own making. The lower Mississippi River, before it was harnessed by man, was and yet is to some extent, a conspicuous example of this. In such a stream any steep bank is readily caved by scour at its toe, but the materials that compose it, if built up in the form of a bar having a flat top and slopes of one on 40 or flatter, once thoroughly compacted, offer great resistance to flowing water even during major floods. Should such a bar grow in height sufficiently to project above low-water level, vegetation of many kinds, chiefly willows, take root and the upbuilding process thereafter proceeds at a faster rate. Nothing can stop its progress except, in time, a change in current-direction due to channel-shifting, which may erode the bar at some point and give it a steep face. Once this face becomes steep enough to cave, the bar is doomed for removal, for nothing can stop the caving, except possibly a further change in channel-direction causing the formation of new deposits. These processes are matters of common observation and confirm the principle in stream-dynamics that, normally, bed-changes result from bank-changes, and that only under special conditions is the reverse true.

In the arid regions, where many stream-beds are normally dry for many months each year, compaction of bed- and bar-materials is greatly interfered with through wind, sunlight, and oxidation of organic matter. Such beds, including those of arroyos, are notorious for the mobile character of their materials. It seems as if nature here compensates for the lack of stream-flow by keeping bed-materials in unconsolidated form, readily moved when flow does occur. As rainfall in the arid regions is usually torrential while it lasts, stream-discharge is of the flashiest type, changing from zero to high stages and back to zero in short periods of time. Nearly all of the lesser streams in Arizona and New Mexico depend for the movement of their sediment-load on runoff of the cloudburst type, which occurs on an average not oftener than once a year or once in many years. It should follow that the streams of the arid regions are great sediment-carriers in time of flood. This is borne out by the Gila and Salt rivers, and the Colorado River, reputed to be the greatest sediment-carrying rivers in the United States. All dry stream-beds lose materials through wind-action. The amount of sand blown out of some river-beds assumes large proportions, a remarkable instance being the Cimmarron River in Oklahoma which has high wind-blown sand-hills skirting it for many miles. Here, again, lack of transporting power by water is offset in some degree by wind-erosion.

High stages, such as remove sediment-accumulations, do not ordinarily occur simultaneously throughout all the arteries of any one river-system. Normally, the rains that cause the greatest rates of discharge in rivulets and small streams are summer occurrences of local thunder-storm and cloudburst origin, and cause only minor rises in the larger streams (G. H. Matthes, Floods on small streams caused by rainfall of the cloudburst type, Trans. Amer. Soc. Civ. Eng., v. 85, 1922, pp. 1388-1399). Vast quantities of debris transported at such times by the smaller streams are then dumped into the parent stream-channel, there to lie spread out in fan-shaped deltas awaiting removal by high stages in the parent stream. The writer, from observation, has known debris-fans and deltas to require an entire year for their removal by successive floods. Obviously, the process of their removal varies, depending upon the frequency, magnitude, and duration of floods in the parent stream, and also upon the nature of the debris and the extent to which it becomes compacted. The important point is that debris accumulations at the mouths of small tributaries require flood-flow for their removal. Low and ordinary stages may chisel at such deposits but can not transport the materials, if at all, farther than into the nearest pool. Debris accumulations at the mouths of large tributaries behave differently from the fans and deltas created by small streams, because the material is delivered over longer periods. This causes bars and sometimes islands to form in the main stream below the mouths of such tributaries. Flood-flow may succeed in transporting such deposits when channel-conditions are exceptionally favorable. More often, the main stream is unable to move all of the debris and is forced through flood-flow to widen and maintain a divided channel with islands or bars interspersed.

The most effective forms of kinetic energy affecting debris removal are turbulence and tractive force. Natural stream-flow is more or less turbulent at all stages but this increases rapidly as depths and water-surface slopes increase. Tractive force, exerted by flowing water along stream-bottoms, propels the heavier mobile bed-materials, and is directly proportional to depth as well as slope. Turbulence manifests itself principally in upward currents, and acts as a lifting agency which not only tears loose both fine and coarse bed-materials from their compacted state, but keeps suspended materials in suspension and also causes part of the bed load to progress by saltation. Among the secondary agencies that destroy the cohesion of compacted materials, abrasion figures prominently. It is caused by the impact of the coarser bed-load particles, which erodes the most resistant sedimentary materials including the hardest rocks.

All of the energy-forms described, and a number of lesser ones not mentioned, become most active at high stages. Normally, any stream develops its most efficient tractive force as well as its greatest turbulence when its cross-section is flowing full. That is, the forces then expended in debris removal are greatest for the volume of water flowing. Over-bank stages may cause greater energy-values by virtue of added depths, but not commensurately with additional discharge.

It should be added that small channels cut through bars during low stages, especially at cross-overs, are not a form of debris removal. Erosion of this kind is only a local displacement of relatively small volumes of material. These still require flood-stages for their eventual removal.

The situation in the United States today with respect to the effects of river-utilization on stream-channels may be summed up as follows. Existing flood-control works have caused but little impairment to stream-channels, but more comprehensive developments, such as storage of flood-waters for use in irrigation or in power-production are beginning to produce deleterious effects. The harm that has resulted so far is not calamitous, because the offending works have not been in operation long enough to produce marked effects. However, the indications are that this country must look forward to channel-deterioration of the kind that has developed in Europe, where intensive stream-flow utilization has been in effect long enough to make such troubles of growing importance.

The more completely a river-system is developed with respect to navigation, flood-control, irrigation, power, and domestic water-supply, the greater the dangers of upsetting the physiographic balance are likely to be. In the modern concept of comprehensive stream-flow utilization, all water is put to some form of beneficial use for man, and channel-maintenance is most often taken for granted. There is no real excuse for this, as intelligent operation of comprehensive river-development works, properly planned, can be made to provide for flushing stream-channels at appropriate times. The problem is more complex in the arid western states where water is scarce and has a high value, than it is in the more bountifully supplied eastern states.

River-channel deterioration partakes mainly of two forms: (1) Loss of carrying capacity for both water and solids, caused by elimination of high stages, and (2) excessive bed-erosion caused by lack of sufficient bed-load needed to use up the kinetic energy normally expended in debris transportation. Diametrically opposite as these two forms may be, they may develop in different parts of the same stream. Each is accompanied by changes in hydraulic gradients which, taken in conjunction with the changes in cross-section, may serve to alter the regimen of a stream drastically. The many and varied aspects involved are beyond the scope of this paper. The following is believed to be helpful in visualizing the effects which, experience indicates, result from different modes of river development.

(a) Levees confine flood-discharge and by increasing channel-depths increase both tractive force and turbulence. The net result is better carrying-capacity for both water and debris load, also greater erosive effects on bed and banks. Experience has shown levees to be more beneficial to channel-maintenance than otherwise.

(b) Canalization, if effected by locks, and dams of the collapsible type which may be made virtually nonexistent during high stages, affords little or no interference with the natural processes of sediment-transportation, although small local deposits at the structures may be inevitable.

(c) Retarding basins of the gateless automatic type devoted exclusively to flood-control may cause gradual accumulations of sedimentary materials to form in the river-beds below them, due to too great reduction in stages and virtual elimination of bank-full discharges. The latter can occur only during the greatest floods for which the system is designed, and therefore are not likely to happen often enough to keep channels cleaned out.

(d) Flood-control reservoirs of the gate-controlled type permit of effective flushing out of stream-channels and, if operated intelligently, cause a minimum of interference with channel-maintenance.

(e) Cut-offs and channel straightening increase water-surface slopes, increase carrying capacity for both water and sedimentary load, and, under certain conditions, tend to increase the erosive effects on bed and banks.

(f) Reservoirs for two or more uses, such as power and flood-control, power and irrigation, or flood-control, navigation and power, are likely to affect channel-capacities materially. They are designed to utilize the available yield from the watersheds above them with greatest practicable efficiency. This implies that only during extraordinary storms would water pass over their spillways in sufficient volume to remove debris accumulations in river-channels below. Such occasions would be too infrequent to prevent channel-deterioration. The following conditions may develop as the result of their operation:

(1) Reservoirs of this kind, if built on small streams, intercept large quantities of coarse debris and thus relieve the stream on which they are built, as well as the parent stream, of an appreciable proportion of bed-load. This may be a benefit to the parent stream, but becomes detrimental to the small stream by causing the latter's channel to scour unduly for want of sufficient bed-load to use up its tractive force. Sill dams at suitable intervals will check this.

(2) Reservoirs of this kind, if built on a large stream, are certain to cause unbalanced conditions downstream. By intercepting the bulk of the bed-load and an appreciable part of the suspended load, excessive scour is induced in the reach next below such a reservoir, caused by lack of sufficient bed-load to use up the available tractive force; second, permanent debris accumulations in the lower reaches of the stream are caused by lack of high stages to move the sediment-load resulting from the excessive scour referred to, plus that contributed by uncontrolled tributaries emptying into the stream below the reservoir. This latter condition tends to grow progressively worse as the distance below the reservoir and the number of uncontrolled tributary inflows increases, and if permitted to reach an advanced stage can be recti-

fied only at considerable cost.

Power dams of moderate height are less harmful than high dams which are effective flow-equalizers. Most run-of-river power-plants are beneficial because during high stages they do not interfere with stream-flow, while during low stages, when they are operated for peak-load production, their high rates of discharge over short periods are of material assistance in keeping river-channels flushed out.

To what extent the natural flushing action of flood-flows can be curtailed in any given river-system without upsetting the equilibrium between soil-erosion, runoff, and debris-carrying capacities, is entirely within range of practical predetermination. The problem calls for study of the materials that are transported under normal conditions, their tendency to accumulate, and their susceptibility to compaction. It calls for study of the discharges required to develop erosive and transporting forms of energy necessary for debris removal, and of the frequencies with which various flood-flow intensities have occurred in the past. It calls for study of soil-erosion conditions, and the possibilities of checking excessive erosion, thereby lessening the volumes of water required for future channel-maintenance.

Office of the President,
Mississippi River Commission,
Vicksburg, Mississippi

A STUDY OF SALT-WATER ENCROACHMENT IN THE GALVESTON AREA, TEXAS

Samuel F. Turner and Margaret D. Foster

A survey of the ground-water resources of the region in which Houston and Galveston are situated was started in December 1930 by the United States Geological Survey in cooperation with the Texas Board of Water Engineers. In connection with this survey a special study is being made of the geochemical relations of the ground-waters of an area about 25 miles wide and 90 miles long, extending from Galveston northwestward through Houston. This study considers the influence on the ground-waters of the age and degree of weathering of the outcrop formations, base-exchange materials, salt-domes, and salt-water encroachment. In this paper, however, attention is confined to salt-water encroachment along the line from Galveston to Houston (Fig. 1).

The area between Galveston and Houston is underlain by unconsolidated beds of permeable but somewhat fine-grained sands and relatively impermeable clays of Pliocene and Pleistocene age, belonging to the Lagarto, Goliad, Lissie, and Beaumont formations (Fig. 2A). The upper part of the Lagarto clay, the oldest of these formations, is composed largely of calcareous clays and shales. Both the Goliad sand and the Lissie formation contain alternating beds of sand and clay, with the sand predominating in the lower part of each formation and the clay in the upper part. The Lissie, however, is much more calcareous than the Goliad. The Beaumont clay consists mainly of calcareous clay but includes two thick, persistent sands--one at the base and one near the center--with thinner sands in the clay-layers. The Recent deposits are composed of sand, clay, and shells. The clay-layers in all the formations appear to be persistent and are relatively impermeable. They therefore act as confining beds holding the water in the permeable sands under artesian pressure.

A hypothetical geologic section extending from Galveston southward to the edge of the continental shelf is shown in Figure 2B. The position of the bottom of the Gulf of Mexico with relation to sea-level was taken from a navigation-chart of the Gulf prepared by the United States Coast and Geodetic Survey. The formations were drawn by taking their known depths and thicknesses at Galveston and extending them to the edge of the continental shelf, continuing the thinning of the sands and the lessening of the dip that is shown from Houston to Galveston. In this projection the middle sand in the Beaumont crops out on the edge of the continental shelf at about 1300 feet below sea-level, the basal sand of the Beaumont at 1800 feet, the basal sand of the Lissie at 2100 feet, and the basal sand of the Goliad at 2500 feet. This is believed to be the most probable arrangement, but the formations may crop out on the edge of the continental shelf at greater depths, or they may bend upward and crop out at lesser depths, possibly before reaching the edge of the shelf. They may even pinch

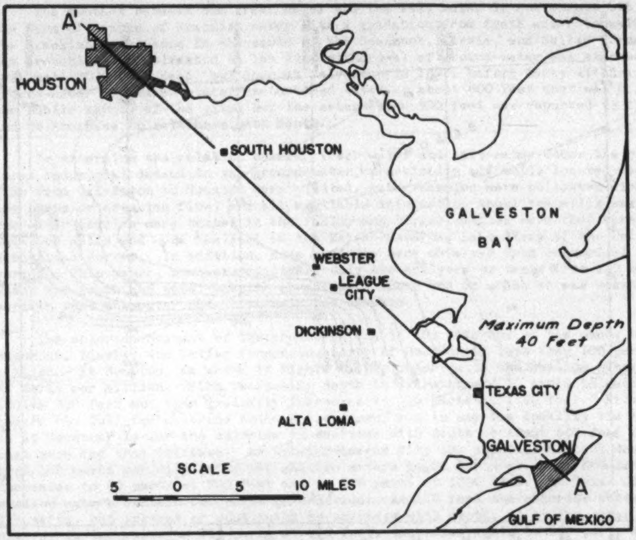
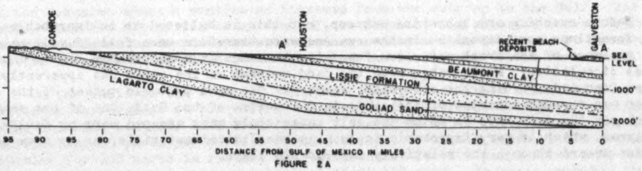

A'
HOUSTON
SOUTH HOUSTON
GALVESTON
BAY
WEBSTER
LEAGUE CITY
DICKINSON
Maximum Depth 40 Feet
TEXAS CITY
ALTA LOMA
GALVESTON
A
SCALE
5 0 5 10 MILES
GULF OF MEXICO

Fig. 1--Map showing location of section studied


CONROE
HOUSTON
GALVESTON
A'
RECENT BEACH DEPOSITS
A
SEA LEVEL
BEAUMONT CLAY
LISSIE FORMATION
LAGARTO CLAY
GOLIAD SAND
-1000'
-2000'
95 90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
DISTANCE FROM GULF OF MEXICO IN MILES
FIGURE 2A

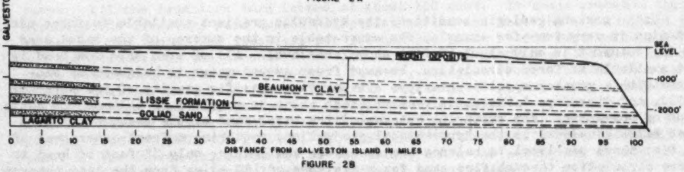

GALVESTON
SEA LEVEL
RECENT DEPOSITS
-1000'
BEAUMONT CLAY
LISSIE FORMATION
GOLIAD SAND
LAGARTO CLAY
-2000'
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
DISTANCE FROM GALVESTON ISLAND IN MILES
FIGURE 2B

Fig. 2A--Generalized geologic section from Conroe southeastward through Houston to Galveston

Fig. 2B--Hypothetical geologic section from Galveston southward to the edge of the continental shelf

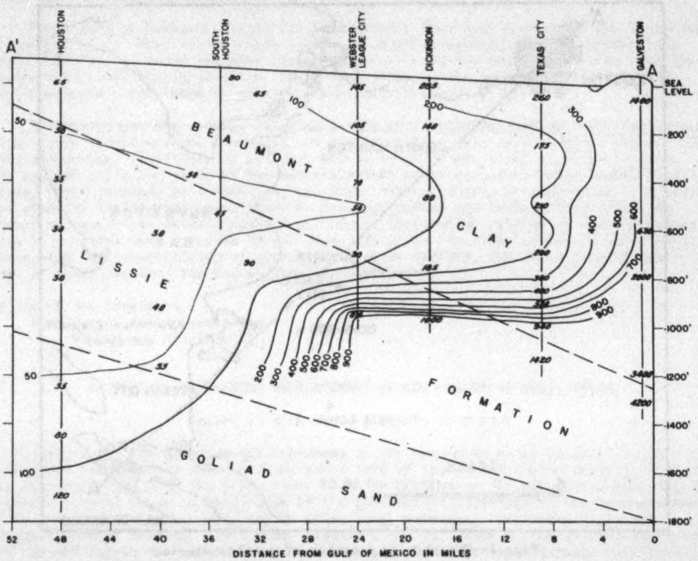


Fig. 3--Generalized section from Galveston to Houston showing lines of equal chloride-content of the ground-water in parts per million

out before reaching any submarine outcrop, but this is believed to be improbable. As the formations were deposited in the sea and were therefore once full of salt-water, the presence of the fresh water now found in the sands at considerable depths indicates circulation. Fresh water from the land outcrop of the sands has apparently moved downward, forcing the salt-water seaward. The most probable outlet of the salt water was through outcrops of the sands in the bottom of the Gulf, but if the sands pinch out the only ways in which the salt water could have escaped were by fault-fissures, which is very improbable in such unconsolidated materials, or by slow percolation upward through the relatively impermeable clays.

Under present geologic conditions the hydraulic gradient available to force circulation is very low--for example, the water-table in the outcrop of the basal sand of the Beaumont is only about 80 feet above sea-level. All of even this low head is not available to force circulation, because fresh ground-water is balanced by sea-water with a greater specific gravity. The average specific gravity of sea-water is 1.024, and therefore 1.024 cubic feet of fresh water is required to balance one cubic foot of sea-water. The submarine outcrop of the basal sand of the Beaumont is 1800 feet below sea-level in the hypothetical projection, requiring a fresh-water head of 43 feet above sea-level to balance the sea-water and leaving only 37 feet of head to force circulation through fine sand for a distance of 160 miles from the land outcrop to the submarine outcrop. This would give a hydraulic gradient of only about three inches to the mile, and any movement taking place would be very slow.

There is evidence that within comparatively recent geologic time the sea has stood both higher and lower with reference to the land-surface than at present. When the sea stood lower the seaward movement of the ground-water was quickened; when it stood higher the seaward movement became slower, or there may have been a reverse movement with sea-water invading the water-bearing sands.

The contact between the fresh water and the salt water is not abrupt but is in the form of a zone of brackish water with a gradation from fresh water to salt water. The brackish-water zone in the sands of the Beaumont, Lissie, and Goliad formations was probably near Galveston at the time withdrawal of ground-water was started. A test-well 3070 feet deep, put down at Galveston in 1892, before heavy withdrawal of ground-water had taken place, encountered water at about 800 feet that was used for the public supply of the city, but the water below 800 feet was reported to be salty and to increase in saltiness with depth.

To determine the relation between fresh water and salt-water under the present large industrial demand on the ground-water, practically all wells located near the line from Galveston to Houston were visited, water-samples were collected direct from the pumps or artesian flow, and all available information about the wells was obtained. The water-samples were tested in the field, and larger samples were then taken from selected wells and were analyzed in the Water-Resources Laboratory of the United States Geological Survey. In addition, some analyses were obtained from commerical laboratories. This paper, however, considers only the analyses or tests from 130 wells for which the depth and water-bearing strata were known and in which it was reasonably certain that the water came from only one stratum.

The chloride content of the ground-waters in the outcrops of the sands of the Beaumont, Lissie, and Goliad formations north of Houston is less than 100 parts per million. At Houston, as shown in Figure 3, the chloride in the shallow waters averages 65 parts per million. With increasing depth it decreases to 30 parts in waters from 500 to 800 feet and then gradually increases to 120 parts at 1700 feet. From Houston toward the Gulf the chloride content increases, but in any one locality the tendency, as at Houston, is for the chloride to decrease with depth to about 500 feet or somewhat more and then increase. At Webster-League City the chloride content decreases from 145 parts per million in the shallow waters to 50 parts at about 500 feet, then increases to 90 parts at 700 feet and to 870 parts at 1000 feet. At Texas City the shallow waters contain 260 parts of chloride. At 250 feet the chloride content is 175 parts, but instead of continuing to decrease with depth, as at the other two places, it increases to 210 parts at 500 feet, decreases again to 200 parts at 700 feet, and then increases to 940 parts at 1000 feet and 1420 parts at 1150 feet. At Galveston the best water sampled was at 600 feet and contained 630 parts of chloride. From that depth the chloride content increases to about 3400 parts at 1200 feet and about 4200 parts at 1300 feet. The chloride content of the water in each of the sands in the Beaumont shows a continuous increase from the outcrop to the Gulf. For example, down the dip of the basal sand of the Beaumont the chloride increases from 50 parts at Houston to 90 parts at Webster-League City and to 940 parts at Texas City. A similar increase takes place in the sands of the Lissie and Goliad formations.

On the basis of the chloride content of the ground-waters along the line from Galveston to Houston, as plotted on the section in Figure 3, isochlors, or lines of equal chloride content, have been drawn. It will be noted that, whereas the isochlor representing 50 parts per million forms a sharp nose at the depth of 500 feet, the isochlor for 100 parts is rounded and the isochlor for 200 parts forms a reverse curve. All the isochlors turn inland at about 800 feet. It seems probable that normally the isochlors were smooth elliptical curves and that the blunting and reversal of the tip of the isochlors for 100 and 200 parts at 500 feet below sea-level and the flatness of the isochlors for 300 to 900 parts at 800 to 1000 feet are due to heavy withdrawal of the ground-water. However, analyses are not available to show changes that may have taken place since the beginning of ground-water development. That there has been some salt-water encroachment is indicated by the fact that before 1896 the city of Galveston obtained its water-supply from wells on Galveston Island, drawing from the 800-foot stratum, but that in 1896 these wells were abandoned on account of the increasing saltiness of the water, and a new supply was developed at Alta Loma, on the mainland, 15 miles northwest of Galveston.

The tentative program for future work involves the collection and analysis every six months of samples from 12 selected wells. These analyses, with the large amount of definite data on hand as to the present chemical composition of the ground-waters, should serve to determine rather definitely the rate and the direction of any movement of the zone of contact between fresh water and salt water in each of the principal water-bearing beds.

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THE WILTING-RANGE IN CERTAIN SOILS AND THE ULTIMATE WILTING-POINT

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In 1927 the authors initiated a study of rainfall-penetration and consumptive use of water in the Santa Ana River Valley of Southern California [see reference 1 at end of paper]. In connection with this study, a large number of soil-samples have been taken in areas of native vegetation to observe the depth of penetration of rain and to determine the moisture-content of the soil.

In Southern California the major portion of the annual rainfall occurs during the winter months and little or no rain falls during the summer. In some years there are periods longer than nine months in which there is no effective rain. The Xerophytic native vegetation adapted to live through these long dry periods has extensive root-systems that draw on the moisture to great depths and extract the moisture-content of the soil to low values.

One of the principal factors that delimits the depth of rainfall-penetration is the moisture-content in the fall of the year just prior to the rainy season. This factor has been termed the initial fall moisture-deficiency and is defined as the amount by which the actual moisture-content of a given soil-zone (usually the root-zone) is less than field-capacity at the beginning of the rainy season. As data were collected for the initial fall moisture-deficiency, it was noted that the soil would be remarkably uniform in moisture-content to considerable depths and attempts were made to relate the values found to the various physical constants of the soil. It is the purpose of this paper to report the relation of the minimum soil-moisture contents found in the field to laboratory determinations obtained by the wilting of sunflower-plants. The wilting-range is defined and the ultimate wilting-point advanced as a useful base for calculating the amount of moisture in the soil available to plants.

One of the plots used in this study is located on the Cucamonga outwash fan at an elevation of approximately 2100 feet above sea-level. During the period of the test reported here, the area was covered with a dense growth of native vegetation, two to three feet in height for the most part. The dominant plants were identified by Dr. E. M. Harvey of the United States Bureau of Plant Industry and are listed in Table 1.

Table 1--Dominant vegetation on Cucamonga plot

Artemesia Californica	(Wormwood)
Salvia leucophylla	(Purple sage)
Salvia mellifera	(Black sage)
Rhamnus Crocea	(Buckthorn)
Rhamnus Californica	(Buckthorn)
Eriogonium fasciculatum	(Buckwheat)
Lotus scoparius	(Deerweed)
Sambucus Glauca	(Blueberry elder)
Paeonia brownii	(Western peony)
Senesia Douglasii	(- - - - - - - -)

There were several rain-gages located in the vicinity, one being one-quarter mile west of the plot. The pertinent portion of the record of precipitation is given in Table 2. The soil is classified as a Hanford gravelly sandy loam. All soil-samples were screened on a two-millimeter sieve and the moisture-content based on the oven-dry weight of the material passing the two-millimeter sieve. The material retained on the screen was classed as rock. The rock-content of the top two feet was 30 per cent, and from two to 16 feet in depth it was 50 per cent. The soil-moisture record is given in Table 3. The high moisture-contents noted for the winter months are characteristic of conditions after cold winter-rains and illustrate the effect of the temperature of the water on the movement of soil-moisture. The effect is to give high values to determinations of field-capacity made following cold winter-rains.

The vegetation makes active growth during the spring months when the maximum amount of readily available moisture is present. It becomes semidormant in the late summer as the soil-moisture is depleted. The progressive drying of the soil is illustrated in Table 3. By June 25, 1932, the top four feet of soil was below five per

Table 2--Rainfall near Cucamonga brush-plot, 1931-33

1931-32			1932-33		
Date of storm	Rainfall	Total to date from July 1, 1931	Date of storm	Rainfall	Total to date from July 1, 1932
	inch	inch		inch	inch
Jan. 1	....	13.72			
Jan. 1- 3	0.35	14.07	Sep. 29	0.02	0.02
Jan. 13	0.36	14.43	Oct. 1	0.10	0.12
Jan. 16	0.43	14.86	Oct. 9	0.21	0.33
Jan. 21	0.02	14.88	Dec. 8- 9	0.54	0.87
Jan. 27	0.03	14.91	Dec. 11-13	1.87	2.74
Jan. 31 to Feb. 2	3.79	18.70	Dec. 21	0.09	2.83
Feb. 7-19	9.18	27.88	Dec. 23	0.30	3.13
Mar. 4	0.01	27.89	Jan. 16-20	8.06	11.19
Mar. 15-16	0.22	28.11	Jan. 22-23	1.06	12.25
Mar. 21-22	0.11	28.22	Jan. 25	0.22	12.47
Mar. 25-28	0.81	29.03	Jan. 27	0.26	12.73
May 21	0.02	29.05			
June 4- 5	0.32	29.37			

Table 3--Average moisture-content of the soil at Cucamonga brush-plot, 1932-33

Depth of sample	*Average moisture-content of the soil											
	Jan. 25, 1932	Feb. 3, 1932	Mar. 16, 1932	Mar. 29, 1932	Apr. 14, 1932	June 25, 1932	Sep. 2, 1932	Nov. 3, 1932	Jan. 26, 1933	Feb. 4, 1933	Feb. 11, 1933	Nov. 27, 1933
feet	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o
1	16.9	18.5	12.4	8.6	6.1	4.1	3.7	...	13.1	14.9	15.9	3.9
2	18.2	20.8	14.4	11.7	8.2	4.4	4.0	4.1	14.2	16.7	10.8	4.1
3	16.1	17.8	13.4	12.7	10.1	4.5	4.3	4.2	13.6	16.4	15.2	4.1
4	17.5	17.9	13.3	11.9	10.1	4.9	4.4	4.3	12.6	15.5	15.4	4.2
5	15.7	17.0	13.7	14.0	12.4	6.1	4.9	4.2	11.0	14.1	15.4	4.3
6	15.4	16.7	12.7	13.2	9.4	7.5	5.7	4.3	9.9	14.1	15.0	4.6
7	15.3	17.3	13.4	12.9	....	7.8	5.5	4.5	2.5	11.6	14.3	...
8	10.3	16.1	13.3	11.8	10.2	8.5	5.8	4.7	5.0	4.7	14.2	...
9	7.8	13.5	12.9	11.7	11.5	9.3	6.4	5.8	...	5.8	12.9	...
10	7.4	7.0	12.2	12.1	10.7	9.6	7.2	7.1	...	7.1	6.0	...
11	6.7	6.1	11.3	13.5	12.5	10.6	8.1	9.3	...	9.3	...	...
12	7.0	5.6	12.9	12.0	9.8	11.0	9.1	7.3	...	7.3	...	...
13	5.3	4.6	14.8	13.0	12.8	11.7	...	8.3	...	8.3	...	...
14	6.7	...	15.7	16.6	10.7	11.9	...	9.1	...	9.1	...	...
15	8.1	...	15.7	16.3	....	12.4	...	7.2	...	7.2	...	...
16	6.6	...	12.5	12.4	....	....	...	8.9	...	8.9	...	...

*The per cent of moisture-content is based on the oven dry weight of the material in the sample that passed a two-millimeter screen.

cent in moisture-content. By November 3, eight feet of soil was reduced below five per cent, and there was an appreciable reduction in moisture-content from the 16-foot level. On November 3, 1932, the average moisture-content of the one-foot soil-zones from two to six feet, inclusive, was 4.22 per cent. On November 27, 1933, the average for these same levels was found to be 4.26 per cent. This remarkable consistency is similar to results obtained from other plots in previous seasons--a fact which suggested the investigation for a possible relation to some physical soil-moisture constant. Samples for laboratory determinations were collected from the Cucamonga plot November 3, 1932.

The samples were obtained from a dug pit and a 15-pound sample of screened soil was taken from each foot in depth. From each of these large samples, four samples were taken for determination of actual moisture-content, four samples were taken for moisture-equivalents, and four for wilting-point work. The average actual moisture-contents for each foot in depth are given in Table 3.

For the top 12 feet of soil, the average moisture-equivalent was found to be 11.40 per cent, and the average wilting-coefficient 5.55 per cent. The wilting-coefficient determinations were made with sunflower-plants in accordance with the definition of Briggs and Shantz [2]. Briggs and Shantz defined the wilting-coefficient of a soil as the moisture-content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in their moisture-content as the result of a deficiency in the soil-moisture supply. In this definition, special note should be taken of the word "First" as it requires careful work to determine the exact point when a plant first undergoes a permanent reduction in moisture-content. Briggs and Shantz employed an ingenious balancing method for plants that suffer initial losses in moisture-content without visible sign. With sunflower-plants, the first reduction in moisture-content of the plant may be observed in the drooping of the first pair of leaves above the cotyledons. When the lower leaves fail to recover in an approximately saturated atmosphere, the plant is considered to be at the wilting-coefficient. The ratio of the moisture-equivalent to the wilting-coefficient for the Cucamonga plot was found to be 2.05.

If water is not added to the soil when it is at the wilting-coefficient, the plant continues to extract moisture at a restricted rate, and, as the moisture-content of the soil is further reduced, wilt progresses up the plant to higher and higher leaves. Finally the top whorl or apical pair of leaves wilt and when these leaves are completely wilted the plant will soon die unless water is added to the soil. This condition of complete wilt of all of the leaves on the plant, we have chosen to call the ultimate wilting-point. For the top 12 feet of soil on the Cucamonga plot, the ultimate wilting-point was found to be 4.28 per cent. This agrees very closely with the value of 4.22 per cent for the actual moisture-content of the two- to six-foot zone on November 3, 1932, and with the value of 4.26 per cent for November 27, 1933, for the two- to six-foot zone.

This close agreement between the ultimate wilting-point obtained from laboratory determinations with sunflower-plants and the field moisture-content of the soil after a variety of native plants had acted on the soil for over nine months without addition of fresh moisture, suggests that the ultimate wilting-point is a suitable base from which to calculate the available moisture that can be withdrawn by plants. In all of our work with native vegetation we have never found, in samples taken from below the depth affected by surface-evaporation, moisture-contents below the ultimate wilting-point. Apparent variations from this statement have been found with individual samples, but on recheck they have been found to be within the limits of experimental error.

The nature of the soil-moisture reduction against time curves for several soil-types was studied in detail in the following experiment. Two hundred and twenty-five cans were each filled with approximately 500 grams of soil and planted to sunflowers. After the plants had attained a height of from 12 to 20 inches and had four to eight pairs of leaves, the soil was brought up to above the moisture-equivalent and the cans sealed. Thereafter, each can was weighed between the hours of 4 a.m. and 7 a.m. each morning until after the plant had died and the stem turned brown. The plants were graded each day. Determinations were made for the top 12 feet of soil from the Cucamonga plot and the results are shown graphically in Figures 1A and 1B. Each curve shown in Figures 1A and 1B is the record of the extraction of soil-moisture by a single sunflower-plant. The ultimate wilting-point used is the actual value for the particular sample, but the moisture-equivalent and wilting-coefficient used are the average values determined for the particular depth.

The wilting-range is here defined as the range in moisture-content of the soil between the wilting-coefficient and the ultimate wilting-point. It is the range in moisture-content of the soil while the plant is undergoing the progressive stage of wilt from the wilting of the lower leaves to the complete wilting of the entire plant.

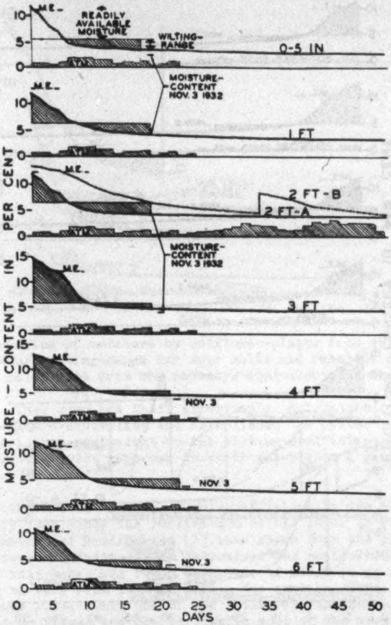

Fig. 1A--Comparison of average moisture-content of soil on Cucamonga plot, November 3, 1932, to rates of extraction of moisture by sunflower-plants from soil in sealed containers by foot-depths from 0 to 6 feet (atmometer records, marked ATM, show relative transpiration-opportunity on different days of sunflower-tests)

The wilting-range for each sample is indicated by the cross-hatched areas above the soil-moisture curves. The readily available moisture above the wilting-coefficient is indicated by the larger cross-hatched area to the left of the soil-moisture curves.

The average moisture-content of the soil on November 3, 1932, is shown for each foot in depth by a horizontal line at the end of the cross-hatched area. The atmometer-records, marked ATM in the Figures, are from a Livingston spherical white atmometer. For the second foot, sample B is the record of the extraction by a young plant with only four small leaves that was allowed to drop well down into the wilting-range and then was rewatered. For the twelfth foot, sample B is the record of a large plant that was maintained with readily available moisture for most of the period of record.

It appears from these records that the roots of the native plants were well established to a depth of eight feet since the field moisture-content was reduced on November 3, 1932, to a value nearly as low as sunflower-plants growing in confined masses of soil. Below eight feet there was still readily available moisture but evidently the root-population was relatively sparse.

Soil-moisture reduction against time curves similar to those in Figures 1A and 1B

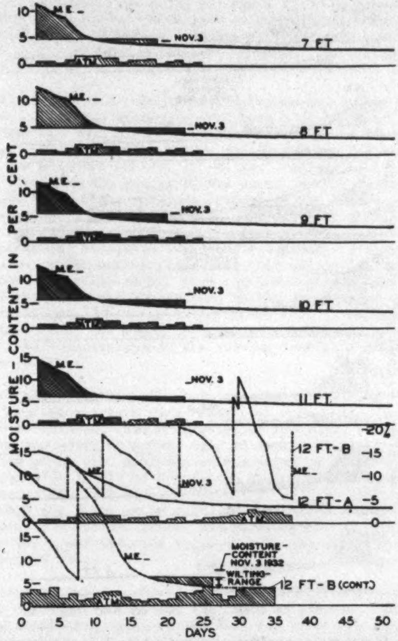

Fig. 1B--Comparison of average moisture-content of soil on Cucamonga plot, November 3, 1932, to rates of extraction of moisture by sunflower-plants from soil in sealed containers by foot-depths from 7 to 12 feet (atmometer-records, marked ATM, show relative transpiration-opportunity on different days of sunflower-tests.

are shown for four soil-types in Figure 2. The wilting-range is shown cross-hatched. The line corresponding to the value obtained by dividing the moisture-equivalent by 1.84 is shown also. It is evident from this illustration that the calculated wilting-coefficient obtained by dividing the moisture-equivalent by the factor 1.84 will not always coincide with the actual wilting-coefficient. This has been pointed out by Veihmeyer and Hendrickson [3].

Briggs and Shantz [2] made wilting-coefficient determinations in a series of 20 soils ranging from sands to clays. In this work, involving about 1300 determinations, a large number of varieties of different crop plants were tested as well as many native plants. The results obtained showed that species differ only slightly as regards the soil-moisture content at which permanent wilting first takes place. They concluded that these differences were so slight as to be without practical significance in the selection of crops for semiarid regions, and attributed the slight differences found to more perfect root-distribution of one variety as compared with another. They pointed out that the moisture-determination for the wilting-coefficient should be made as soon as the plant has first reached a wilted condition from which it cannot recover when placed in a damp chamber. They further concluded that the moisture-equivalent method was the most accurate and satisfactory indirect method of determining the

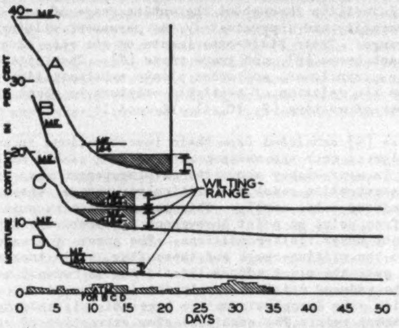

Fig. 2--Rates of extraction of moisture by sunflower-plants from soil in sealed containers showing wilting-range for four soils and relative position of wilting-coefficient calculated from the moisture-equivalent and the factor 1.84

wilting-coefficient. They compared their experimental determinations of the wilting-coefficient to the moisture-equivalent and established the factor 1.84 as the average relationship of the moisture-equivalent to the wilting-coefficient, although the determinations on individual soils reported in their paper show a range from 1.67 to 2.02.

The indirect determination of the wilting-coefficient by use of the factor 1.84 has been rather widely used since the publication of the paper by Briggs and Shantz in 1912. However, Veihmeyer and Hendrickson [3] have shown that the general use of this ratio is open to serious criticism. They determined the residual moisture at permanent wilting on 14 soil-types and found the ratio of moisture-equivalent to moisture at permanent wilting to vary from 1.73 to 3.82. The average ratio for 14 soil-types based on 759 trials was 2.46. Only one of the soils reported showed a ratio below the 1.84 ratio determined by Briggs and Shantz. While most of the work reported by Veihmeyer and Hendrickson was done with sunflower-plants, they state that a number of trials with other plants seemed to substantiate the contention of Briggs and Shantz that on a given soil-type all plants reduce the moisture-content of the soil to about the same extent when permanent wilting is attained.

In an earlier paper [4] Veihmeyer and Hendrickson discuss soil-moisture conditions in relation to plant-growth and review the literature on this subject. They point out that the nature of the wilting-process is dynamic and that various stages of wilt might be recognized since wilting is of a progressive nature. In their definition of permanent wilting-percentage [5], they state that it is the moisture-content below which plants cannot readily obtain water, that it is the soil-moisture condition at which plants wilt and do not recover unless water is applied to the soil. They state further that the permanent wilting-percentage as they use it represents a narrow range of soil-moisture contents within which wilting takes place. Since they recognize the dynamic nature of wilting and define their permanent wilting-percentage as a range of soil-moisture contents within which wilting takes place, their determinations are made at the end of the range they have chosen and must correspond to a point somewhat lower on the soil-moisture reduction against time curve than the "first" point used by Briggs and Shantz. Veihmeyer and Hendrickson set forth the important conclusion that the amount of water available for plant-growth cannot be determined from the moisture-equivalent alone. They advance the opinion that the moisture-equivalent is the best single-valued determination for interpreting the moisture-properties of soils, but it is not an exact measure of how much of that water is available to growing plants. They state that for accurate work the amount of readily available moisture can be obtained only when the amount of residual moisture at permanent wilting is known. Readily available moisture is defined by Veihmeyer and Hendrickson as the moisture above the permanent wilting-percentage [5].

Veihmeyer and Hendrickson conclude from their experiments that water may be used by plants with equal facility throughout the entire range of soil-moisture contents between the field-capacity and approximately the permanent wilting-percentage, that is, above the wilting-range. Their field-experiments on the rate of use of water included prune trees [4], peach trees [6], and grape vines [7]. They cite experiments in Russia with buckwheat, beans, sunflower, and other plants substantiating their work [8]. Field-experiments on the relation of available moisture to plant growth have been reported on by a number of writers [9, 10, 11, 12, and 13].

Furr and Magness [9] concluded from their investigations in apple orchards that the trees can function at near the maximum rate so long as the moisture-content of the whole root-zone is appreciably above the wilting-percentage, but that as the zones of greatest root-concentration reach the wilting-percentage, the tree apparently adjusts itself to a reduced water-supply. This is an important point as variations in root-concentration from point to point throughout the root-zone is characteristic of practically all plants under field-conditions. The zones of greatest root-concentration are first reduced to the wilting-range and thereafter, as an increasing proportion of the root-zone dries out, the plant adjusts itself to the reduced moisture-supply. By the adjustment to the reduced moisture-supply obtained from deep zones of relatively sparse root-population, the Xerophytic native vegetation is able to maintain life over extended periods without rain. The continued slow extraction of soil-moisture from the deeper zones of sparse root-population is illustrated in Table 3 and in Figure 1B. After nine months without effective rain, the moisture-content below a depth of nine feet was still above the wilting-range.

Regarding the lower limits of available moisture, Briggs and Shantz [2] emphasized the fact that their wilting-point did not mark the minimum limit of moisture available to the plant. From laboratory experiments with plants grown in 250 grams of soil, they showed that water was steadily removed from the soil by dying or dead plants and suggested that a limit is reached only when the soil-moisture comes into approximate equilibrium with the moisture-content of the air. They did not submit any evidence to show that such an extreme condition actually occurred in the field. However, Alway [14], and Alway, McDole, and Trumbull [15], report finding the soil below the hygroscopic point in an abandoned olive orchard in Arizona and in the prairies of southwestern Nebraska. Also Batchelor and Reed [16] report that the soil in peach, apricot, and walnut orchards was reduced below the hygroscopic coefficient to great depths when the trees were grown under extremely arid conditions.

More recently Breazeale [17] and Magistad and Breazeale [18] have investigated plant- and soil-relations at and below the wilting-percentage. Breazeale demonstrates experimentally that plants can absorb water from a moist soil, or subsoil, transport this water, and build up the moisture-content of a dry soil. The plant is presented by Breazeale in the rôle of an equalizer of certain natural forces. In accordance with this view, the moisture-content of the entire root-zone will remain above the ultimate wilting-point as long as the plant has some roots in contact with available moisture. This view appears to be substantiated by the work of the present writers.

Shull [19] has measured the force with which moisture is held in the soil in the proximity of the hygroscopic coefficient by the use of seeds, and found it to be of the order of 900 to 1000 atmospheres. It is difficult to conceive of such enormous forces being developed in an active living plant, yet Batchelor and Reed [16] state that in spite of the low moisture-content (below the hygroscopic coefficient) in the latter part of the growing season, the trees showed no permanent wilting but continued to mature and entered the dormant period without apparent injury. Temporary wilting occurred only during the middle of the day when a high temperature was accompanied by a low humidity. It is significant, however, that most of the extremely low moisture-contents reported were found as the trees were approaching dormancy and that following the dry winter of 1917 many of the trees were killed back to the main scaffold limbs. It appears that moisture-contents below the ultimate wilting-point and in the proximity of the hygroscopic coefficient are associated with permanently dry subsoils--a condition similar to plants growing in confined masses of soil in containers. In the present paper the continued loss of moisture through dying and dead sunflower-plants grown in sealed containers is shown in Figures 1A and 1B by the slopes of the lines beyond the wilting-range.

From the foregoing discussion, it appears that soil-moisture is readily available to well-established plants down to the wilting-coefficient as defined by Briggs and Shantz. Below the wilting-coefficient there is a range of moisture-contents in which wilting takes place. The lower limit of this wilting-range has been defined by the authors as the ultimate wilting-point. Under conditions where the plant has no roots in contact with readily available moisture, the moisture-content of the soil may be reduced below the ultimate wilting-point by dying or dead plants or by plants approaching dormancy and may even be reduced to the hygroscopic point under such conditions.

Furr and Taylor [20] have shown that there is a ready cross-transfer of water in lemon trees and that any root may supply water to any branch. Unpublished work by the senior author of the present paper has shown that a sunflower-plant can extract sufficient moisture from one-half or one-quarter of its root-zone to meet the midsummer transpiration demand at Pomona, California, as long as there is readily available moisture in the fraction of the root-zone wetted. In a recent paper, Taylor and Furr [21] have shown that there is an accelerated rate of extraction of soil-moisture from irrigated soil-zones when the major portion of the root-zone is relatively dry. From these facts, it would appear that conditions of water-shortage can not be rationally determined from soil-moisture records and that recourse must be had to the reactions of the plants. Excluding other factors except soil-moisture level, any flattening of curves showing average rate of extraction of soil-moisture must be taken as evidence that some portion of the root-zone has approached the wilting-range, and the problem of the soil-moisture investigator becomes one of determining what portion of the root-zone has approached the wilting-range.

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Bureau of Agricultural Engineering,
U. S. Department of Agriculture,
Pamona, California, April 1934

SOME RELATIONSHIPS OF RUNOFF TO RAINFALL

Caleb Mills Saville

The writer submits some interesting relationships between runoff and rainfall that have come to attention in the course of studies pertaining to water-supply for the Hartford (Connecticut) Metropolitan District. These as well seem generally applicable to similar phenomena in southern New England and perhaps in some other portions of the country.

No claim is made that the correlations here presented offer a solution or even material advancement toward the solution of that complex problem--the relation of rainfall to runoff--which has and must ever present so many varying phases as almost to defy the framing of a formula exact for even local application.

At the present time, a formula for general use seems almost as much of a chimera as that for the Philosopher's Stone of the alchemists--that talisman for transmuting base-metals into precious gold. However, sometimes even a trivial suggestion may lead to a worth-while thought, and the following is presented solely with that end in view.

The basic data are thought to be reliable, having been obtained by standard methods and instruments under more than ordinary careful attention.

The first approach to this study was to determine, as nearly as possible, a satisfactory base from which to work. That most generally used for this purpose, especially where comparatively long-record periods are available, is the average or mean obtained by dividing the sum of the records (samples) by their number.

As is well known and also particularly brought out elsewhere (Saville, J. N.E.W.W.A., v. 47, p. 363 et seq., December 1933), this method results in no firm datum, although in very long-period records the variations (departures) are usually quite small. [This method consists in plotting the maximum and minimum deviations from the normal rainfall for varying periods of observation. As the length of the period is increased, the deviation from the normal decreases.] Nevertheless working from year to year with these, results in differences which, while often too small for practical annual use, are annoying and difficult to handle where careful study is being made extending over a series of years past and into future.

On this account, it is usual to decide on one particular period and designate the average or mean for that period as "normal."

In these studies the "normal" period of the United States Weather Bureau has been used, which is the 50-year average for 1878-1927. It is necessary also to know within certain limits what may be the reliability, as regards constants, of records of varying lengths.

To effect this purpose a study was made of the rainfall record from the West Hartford station (1868-1933) of the water-supply system after the method used by Sir Alexander Binnie (Proc. Inst. C.E., v. 109, p. 58, 1892).

Tables 1 and 2 are abstracted from data appearing in the author's paper referred to above (loc. cit.).

Table 1--Statistical measures for annual rainfall at selected stations, southern New England

[Note--Rainfall figures were obtained from annual summaries published by various water companies; these summaries did not contain information as to number of rainfall-stations used in making up averages for watersheds]

No.	Station	Record		Normal (1878-1927)	Median	Appr. mode[a]	Maximum	Minimum	Variation			Prob. error
		Years	Aver. annual						Stand. σ	Actual	Coefficient	
					inch	inch	inch	inch	inch	o/o	inch	o/o
1	Croton	1868-1933	47.75	48.62	47.22	46.16	63.76	36.28	6.01	±69.7	0.126	1.05
2	Wachusett	1897-1932	44.98	*	44.18	42.58	57.92	34.97	5.96	±63.9	0.133	0.67
3	Wigwam	1908-1923	45.64	*	44.98	43.66	57.37	40.38	4.69	±68.7	0.103	0.79
4	Abbott Run	1907-1932	42.90	*	43.84	45.72	48.53	30.78	4.59	±73.0	0.107	0.61
5	Tucker Br.	1908-1932	47.25	*	46.40	44.70	61.16	38.52	5.77	±76.0	0.122	0.78
6	Sudbury	1875-1932	44.36	44.48	44.10	43.58	57.93	32.78	5.63	±67.3	0.127	0.50
7	Nepaug[c]	1913-1933	43.50	*	42.87	41.61	51.78	34.89	6.62	±76.2	0.152	0.98
	Average[b]	1868-1933	45.50	46.55	45.10	44.30	58.26	35.07	5.71	±69.8	0.126	0.77

*No record. [a] Approximate mode from formula: Mode = Mean - 3 (mean - median).
[b] Weighted average determined by number of years of record for each station. [c] Nepaug station not included on trend-curve of Figure 3.

Table 2--Statistical measures for annual runoff at selected stations, southern New England

[Note--Runoff on Croton, Wachusett, and Sudbury watersheds was determined by the gain or loss in reservoir-storage, taking into account rainfall and evaporation; runoff on Nepaug, Tucker Brook, Abbott Run, and Wigwam watersheds was determined by stream-flow gages, or weirs]

No.	Station	Record		Normal (1878-1927)	Median	Appr. mode[a]	Maximum	Minimum	Variation			Prob. error
		Years	Aver. annual						Stand. σ	Actual	Coefficient	
					inch	inch	inch	inch	inch	o/o	inch	o/o
1	Croton	1868-1932	23.37	23.77	22.87	21.87	39.50	12.39	5.64	±72.3	0.241	0.47
2	Wachusett	1897-1932	23.72	*	22.87	21.17	35.80	13.17	4.91	±77.8	0.207	0.55
3	Wigwam	1908-1923	21.24	*	21.03	20.61	27.33	15.74	3.29	±62.5	0.155	0.55
4	Abbott Run	1907-1932	21.11	*	20.69	19.85	28.46	13.74	3.91	±65.4	0.185	0.52
5	Tucker Br.	1908-1932	24.33	*	22.73	19.53	36.75	15.88	5.10	±80.0	0.210	0.69
6	Sudbury	1875-1932	21.21	21.24	20.88	20.22	36.34	9.46	5.47	±74.1	0.258	0.48
7	Nepaug[c]	1913-1933	22.31	*	21.64	20.30	33.92	11.45	5.23	±81.0	0.235	0.74
	Average[b]	1868-1933	22.54	22.50	21.99	20.89	35.52	12.45	5.07	±73.7	0.224	0.54

*No record. [a] Approximate mode from formula: Mode = Mean - 3 (mean - median).
[b] Weighted average determined by number of years of record for each station. [c] Nepaug station not included on trend-curve of Figure 3.

Table 3--Deviations from normal annual rainfall (43.84 inches) at West Hartford, Connecticut

No. years	Average difference	Maximum	Minimum
	o/o	o/o	o/o
10	10.2	108.8	88.4
20	5.8	107.5	95.5
30	3.0	104.0	97.9
40	1.7	102.6	99.2
50	0.6	100.2	99.0
60	0.8	101.1	98.5

A similar study of the long-period Sudbury (1878) runoff resulted in deviations from average (in this case the average of the periods was used) as shown in Table 4.

Table 4--Deviation from average annual runoff at Sudbury, Massachusetts, watershed (1875-1932)

No. years	Average	Maximum	Period	Minimum	Period
	o/o	o/o		o/o	
10	22.3	119.2	1884-1893	74.6	1908-1917
15	19.3	118.5	1888-1902	80.0	1904-1918
25	11.6	111.5	1884-1908	88.3	1906-1930
30	9.9	110.2	1875-1904	90.5	1903-1932
40	3.4	102.0	1875-1914	95.2	1892-1931
50	0.6	100.4	1875-1924	99.2	1882-1931

From these Tables it appears that,for results generally reliable within two per cent, records of both rainfall and runoff should extend over periods of from 40 to 50 years and that somewhat longer periods are necessary for runoff than for rainfall.

The tabulations in Tables 1 and 2 give the various statistical measures useful in comparing individual characteristics of rainfall and runoff on the several watersheds here considered, and similar data worked up for other watersheds will indicate by comparison the allowances to be considered in comparing and using other data for the same purposes as here employed.

The per cent probable error and the coefficient of variation are most useful for this purpose; the formula for the former is 67.5 times the coefficient of variation divided by the square-root of the number of items, the latter being obtained by taking the square-root of the mean of the squares of the percentage-variations for the period of record regardless of sign.

The following discussion is given in the order in which the several approaches to the problem were undertaken, and, while each step is complete in itself and the items used in the final make-up were identical throughout, the several steps as presented do not always include the same station. The statistical methods used and nomenclature will be found in any standard book on statistical methods.

The early approach to this matter was the combination of representative records and their representation by a frequency-distribution graph (Fig. 1) showing the mean annual runoff in cubic feet per second of seven typical areas with length of records varying from 20 to 65 years. The period includes that from 1868 to 1932 and comprises a total of 253 years; the combined area of the watersheds is 664 square miles, and the mean annual rainfall is 45.69 inches, varying from 42.96 inches at Abbott Run, Rhode Island, to 47.74 inches at Croton, New York.

The frequency-graph of rainfall is shown on Figure 2.

The coefficients of variation for both rainfall and runoff given in Tables 1 and 2 for the several stations used indicate their close agreement in characteristics with each other, and thus quiet any objection that the results obtained from the combination might not be thoroughly representative over the district. To be more assured that all conditions of meteorological importance were covered, however, a period of time much longer than at present available would be required.

As some substitute for this desirable condition, the records of the seven watersheds have been combined as stated above. The more confidence is felt in results obtained because the two longest records, Croton (66 years) and Sudbury (58 years), not only cover these extremely dry periods, namely, 1879-1883, 1908-1912, and 1929-1933, but are at the extreme west and east limits of the district, while the other records, although considerably shorter in length of observation, nevertheless cover the mid-sectional area and they too cover two out of three of the same dry periods, as the longest record.

Attention now is invited to the diagram, Combined watershed relations for selected streams in southern New England, of Figure 3.

The watersheds used in making up this diagram are shown in Table 5.

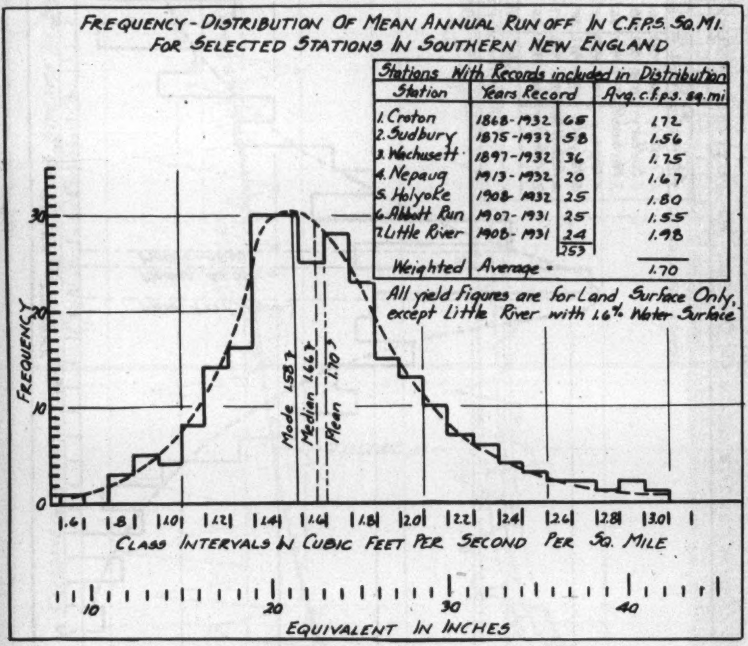
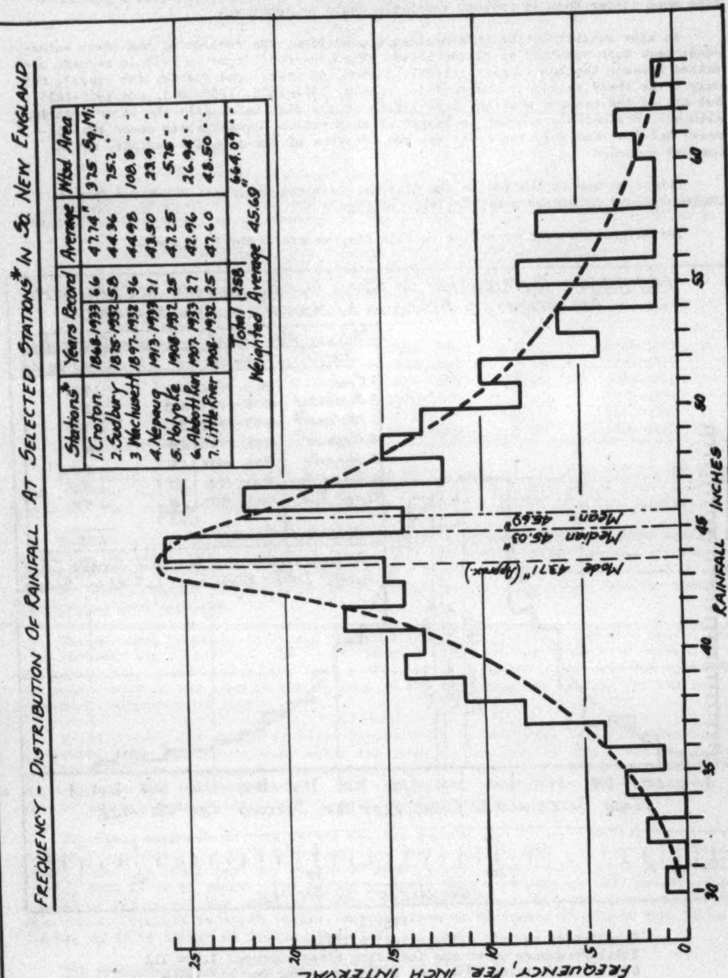


Fig. 1

Location of median: (Mid-value) = 127th)
Total frequency up to and including class interval 1.5 = 111
Class 1.6 contains 25 units, 16 units needed for mid-value
(127th); 16/25 = 0.64 of class 1.6 = 1.66
Mode = Mean - 3 (mean - median) = 1.70 - 3 (1.70 - 1.66) = 1.58



Stations*	Years Record		Average	Wtsd Area
1. Croton.	1868-1933	66	47.74"	375 Sq. Mi.
2. Sudbury	1875-1932	58	44.36	75.2 " "
3 Wachusett	1897-1932	36	44.98	108.0 " "
4. Nepaug	1913-1933	21	43.50	23.9 " "
5. Holyoke	1908-1932	25	47.25	5.75 " "
6. Abbott Run	1907-1933	27	42.96	26.94 " "
7. Little River	1908-1932	25	47.60	48.50 " "
	Total	258		664.09 " "
	Weighted Average		45.69"	

Fig. 2

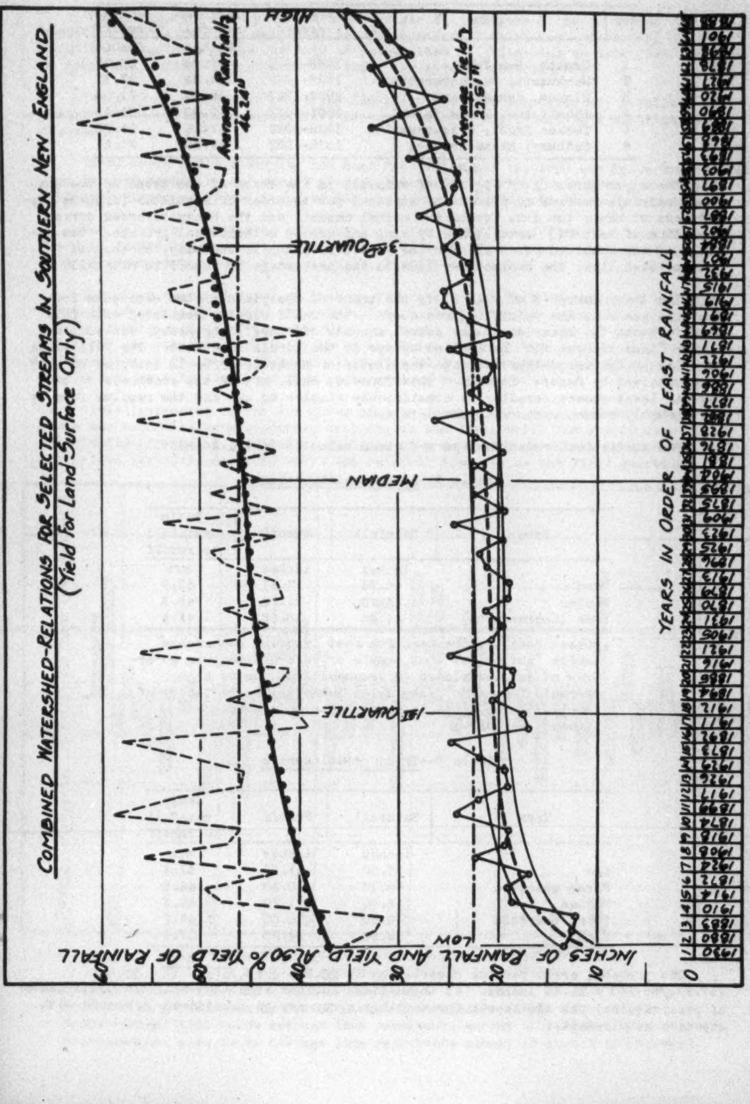

COMBINED WATERSHED-RELATIONS FOR SELECTED STREAMS IN SOUTHERN NEW ENGLAND
(Yield for Land-Surface Only)
INCHES OF RAINFALL AND YIELD ALSO % YIELD OF RAINFALL
0
10
20
30
40
50
60
70
HIGH
3RD QUARTILE
MEDIAN
1ST QUARTILE
LOW
Average Rainfall 46.28 In.
Average Yield 22.61 In.
YEARS IN ORDER OF LEAST RAINFALL
1930
1880
1885
1910
1914
1872
1924
1908
1918
1874
1899
1917
1926
1929
1873
1892
1911
1912
1894
1886
1916
1921
1905
1931
1870
1879
1913
1896
1925
1923
1909
1875
1895
1902
1881
1876
1928
1882
1877
1886
1906
1922
1871
1869
1891
1919
1915
1932
1907
1884
1902
1887
1900
1897
1903
1893
1866
1889
1890
1920
1927
1878
1898
1901
1888

Fig. 3

Table 5--Watersheds used for Figure 3

No.	Name	*Years of record	Average rainfall	Average runoff
			inches	inches
1	Croton, New York	1868-1932	47.74	23.37
2	Wachusett, Massachusetts	1897-1932	44.98	23.72
3	Wigwam, Connecticut	1908-1923	45.64	21.24
4	Abbott Run, Rhode Island	1907-1932	42.90	21.11
5	Tucker Brook, Massachusetts	1908-1932	47.25	24.33
6	Sudbury, Massachusetts	1875-1932	44.36	21.21

The upper curve (A of Fig. 3) of rainfall is the trace of the trend of the combined rainfall-records of all of the stations put in order of magnitude (dryness) regardless of time; the dots locate the actual amount, and the heavy reversed curve, the "line of best fit" established by eye, and not by mathematical process. The average of the combined rainfalls for the period is shown in the heavy horizontal dot-and-dash line; the broken wavy line is the percentage of runoff to rainfall.

The lower curve (B of Fig. 3) is the trend of the yield of the watershed for the same years as the rainfall given above. The small circles connected with full line indicate the location of the actual amounts of runoff; the heavy, dotted line is the "line of best fit" as applied by eye to the circle locations. The full lines parallel to the trend-line indicate the limits of probable error in location of that line obtained by Peters' formula. This formula, while not of the exactness of the regular least-square formula, is considerably simpler to use and the results from it are probably commensurate with the data used.

The statistical relationships are given below in Tables 6 and 7.

Table 6--Actual relationship

Term	Rainfall	Runoff	Ratio rainfall to runoff
	inches	inches	o/o
Mean	46.24	22.51	48.7
Median	45.70	21.20	46.3
Mode (approximate)	44.62	18.58	41.6

[Note--"Mode" is the term for most frequent occurrence while "median" is that sample or record midway in an array of samples placed in sequence from low to high; formula for "mode" (see Yule, Introduction to theory of statistics, p. 121) is approximate mode = mean - 3 (mean - median).]

Table 7--Trend relationships

Term	Rainfall	Runoff	Ratio rainfall to runoff
	inches	inches	o/o
Low	37.00	11.60	31.4
First quartile	43.10	20.20	46.8
Median	45.70	21.20	46.3
Third quartile	48.80	24.00	48.2
High	59.00	34.20	57.9

The probable error for one observation is $\pm 0.845\ \Sigma V/\sqrt{n(n-1)} = \pm 0.845\ 117.9/\sqrt{65(64)} = \pm 1.54$ inches. As these lines enclose about one-half the total number of observations, the limits set for probable error may be considered in accord with standard requirement.

The coefficient of variation is 0.224 inch.

The irregular dotted line, marked "o/o yield" in Figure 3, is of course representative of the ordinary ratios of runoff to rainfall which are interesting in their vagaries as indicating the futility of using these relationships to establish a general correlation-formula applicable to these two natural occurrences.

It is to be noted that the trend-lines are not even approximately parallel, and their curvatures also are dissimilar, although each is approximately symmetrical about its median.

It is worth while observing how much the median and the mode are below the average line in both rainfall- and runoff-trends, thus agreeing with their position in the frequency-curves of Figure 2 and of Figure 1 and indicating the tendency of yield.

The relative position of the crossing-point of the trend-lines and the average lines is interesting, as well as the slope of the two trend-lines, as indicating the rôle of ground-water storage on yield as rainfall decreases.

The sharp downward curve of the runoff-trend to the left of the first quartile and lack of parallelism with the rainfall is indication of the exhaustion of ground-storage during periods of low rainfall, while the upward departure of this curve at the other end--that is, to the right of the third quartile, and its more nearly parallel position to the rainfall-trend--indicates full ground-water, a condition more nearly analogous to discharge from an impervious surface.

Close inspection of the low curve of trend between the first and second quartiles shows the rainfall-curve gradually dropping to the left, while the runoff-curve is practically horizontal, indicating fullness of ground-storage which, apparently, does not become seriously depleted until the rainfall drops below the first quartile.

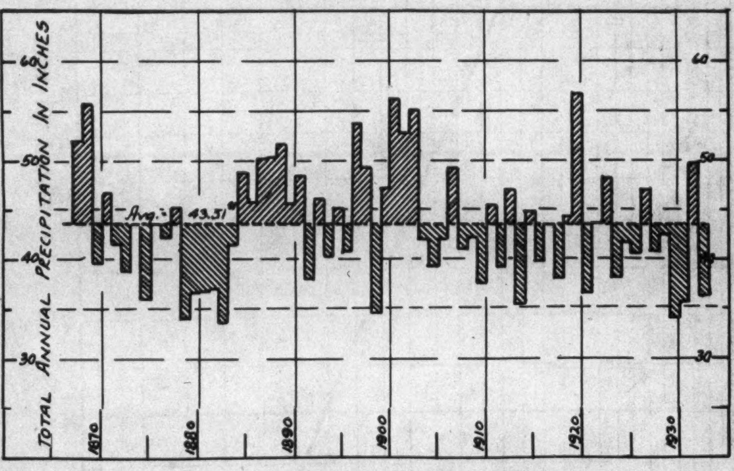


Fig. 4--Rainfall at Reservoir No. 1, West Hartford, for years of record (1868-1933, inclusive)

Mean for years of record = 43".51 (1868-1933)
Normal (for period used by United States Government) = 43".84 (1878-1927)
Cross-hatched area below average line represents amount of deficiency of rainfall
Cross-hatched area above average line represents amount of excess of rainfall

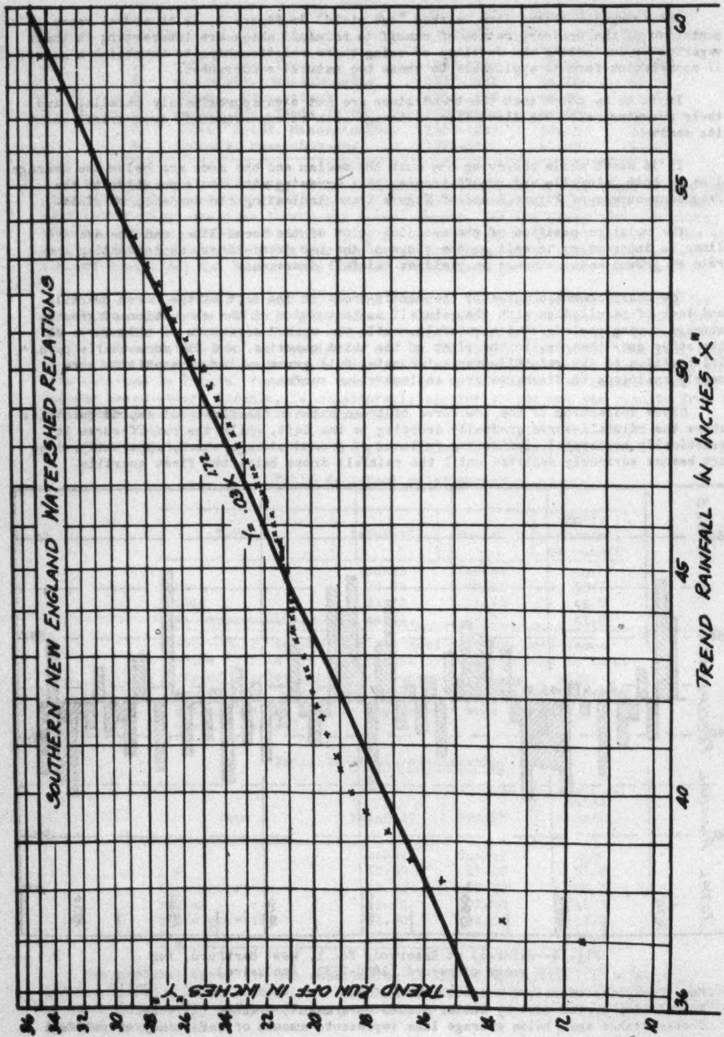

SOUTHERN NEW ENGLAND WATERSHED RELATIONS
Y = .03 X 1.72
TREND RAINFALL IN INCHES "X"
TREND RUN OFF IN INCHES "Y"
36
40
45
50
55
60
36
34
32
30
28
26
24
22
20
18
16
14
12
10

Fig. 5

In other words, for rainfalls in southern New England the critical period for evidence of drought-conditions, so far as it affects water-supply, appears to be about No. 17 (1911), and annual rainfall in amounts less than 43.1 inches--which was the average over the section for each of these years--may be a matter of some moment.

Previous to this critical point, water-supply may not be seriously affected, although vegetation may suffer due to seasonal lack of rain.

It is to be remembered in discussing this matter, however, that the remarks made above apply only to single-year records and a glance at the 65-year record of West Hartford Station (Fig. 4) shows that the high and low rainfall-years are generally well distributed among each other.

In only two periods, 1879-1883 and 1930-1931, have there been consecutive low rainfall-years of serious consequences over the whole section.

The general relationship between these two trend-curves is shown in Figure 5, which is given as a suggestion of what more extreme drought-conditions than any yet experienced may mean to water-supply works, and it is well to keep in mind the rule of rainfall-relationship that minimum is approximately one-half maximum.

To be sure, a probability-curve will show that these conditions are of very rare occurrence, but even so, in the case of important communities, careful consideration of even this happening cannot safely be neglected and good judgment is required to decide how far provision should be made to meet them. It may be 500 years away; it may be around the corner.

It is instructive to note that the years 1911 and 1912 were the only two consecutive low-yield years in the array (Fig. 3), and, as these are located in the lower register, they indicate that this period was the one of most widely spread drought in this section during the period of record.

This period, however, was not the lowest in individual stations. For the easterly portion of the district, the Sudbury, Massachusetts, watershed recorded its lowest two-year (calendar) rainfall-period in 1882 and 1883, while for the Croton, New York, watershed in the westerly section the period 1917-18 averaged the lowest. Both of these periods averaged about 81 per cent of the average at the individual stations.

While rainfall seems the best index at present of runoff-conditions, it should be recognized that lowest runoff-periods are not concomitant with lowest rainfall.

For example (Saville, J. N.E.W.W.A., December 1933), the lowest two-year runoff-period on the Croton Watershed was that of 1880-81 and on the Sudbury watershed was that of 1909-11. [The average runoff on the Sudbury watershed for years 1910-11 equals 12.33 inches, or 58.1 per cent of the average. The average runoff on the Croton watershed for the period 1880-81 equals 15.36 inches, or 65.8 per cent of the average.] At the present time the curves of Figures 3 and 5 are presented as a suggestion which may or may not be helpful for use in the study of runoff-phenomena.

Sufficient grounds for its use, if any there are, can be assured only after a study has been made of dry periods in series comprising longer periods than one year.

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TURBULENCE AND THE TRANSPORTATION OF ROCK DÉBRIS BY STREAMS

John Leighly

(Abstract)

An earlier paper by the author (Toward a theory of the morphologic significance of turbulence in the flow of water in streams, Univ. Calif. Pub. Geogr., v. 6, No. 1, 1932) presented a method of computing the distribution of intensity of turbulence in

the plane cross-section of a stream, from surface-slope and distribution of velocity in the cross-section. In the present paper the results of such computation are compared with the results of computing the same measure of intensity of turbulence from measurements of turbidity by an equation derived by W. Schmidt (Der Massenaustausch in freier Luft und verwandte Erscheinungen, p. 62, 1925). This equation relates the vertical distribution of suspended matter in a column of turbulent fluid to the intensity of turbulence within the same column. The results given by the two procedures are in qualitative agreement. Moreover, assuming a typical vertical distribution of intensity of turbulence, the Schmidt equation, applied to the several fractions of a complex sample of suspended silt, gives results agreeing with the data of measurement such as those published by L. G. Straub (Trans. Amer. Geophys. Union, 1932, p. 379).

In so far as the translocation of rock debris by streams depends upon suspension, it is determined by the distribution of intensity of turbulence in a given stream cross-section, and by the behavior of suspended silt with respect to this distribution. Along lines normal to the bed and to surfaces of equal velocity, the relation of turbidity to turbulence is defined by the Schmidt equation or by that derived by M. P. O'Brien (Trans. Amer. Geophys. Union, 1933, p. 490). Movement of suspended matter in the plane cross-section parallel to the bed and to surfaces of equal velocity is a process of diffusion along gradients of turbidity. If turbulence is sufficiently intense to cause a part of the bed-material to diffuse upward into suspension, the maximum turbidity is attained in those columns of water in which the gradient of intensity of turbulence, measured from the bed, is at a maximum. The suspended silt diffuses horizontally from these columns of maximum turbidity; its further fate depends upon the gradients of turbulence and velocity along the paths of diffusion. The evidence at hand indicates that with respect to the diffusion of suspended silt through the plane cross-section of a stream three regions of contrasted characteristics may be distinguished:

(1) An axial region of maximum velocity and moderate intensity of turbulence. Silt is diffused into this region from the two flanking regions of maximum turbidity, and is disposed of by suspension in the relatively large quantity of water available in unit time.

(2) Two regions flanking region (1) on either side, the loci of most intense turbulence and of maximum gradient of intensity of turbulence from the bed into the body of the stream; hence also the loci of maximum turbidity and of erosion of the bed. From these flanking regions suspended silt may diffuse toward the axial region or toward regions (3)--that is, toward the center or toward the sides of the channel.

(3) Two lateral regions, of indefinite extent from regions (2) toward the sides of the channel or into a larger mass of water through which the thread of maximum velocity, lying in region (1), runs. In regions (3) both velocity and intensity of turbulence are low; they are therefore the loci of deposition. Lateral diffusion and consequent deposition may be prevented by the resistance of a component of gravity parallel to the sides of the channel.

[The full text of the paper will be published under the same title in Geographical Review, New York, v. 24, No. 3, July 1934.]

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EFFECT OF CHANNEL-CONTRACTION WORKS UPON REGIMEN OF MOVABLE BED-STREAMS

Lorenz G. Straub

When water flows in an open channel having an erosible bed a condition of equilibrium is approached in which the water ceases to cause further erosion of its bed, although sedimentary material is continuously transported by the stream. Various control-measures required to improve the conditions of a river-system for use in navigation, irrigation, and power-development set up a new regimen or condition of equilibrium of the system. Thus, for example, channel-contraction works (structures used for narrowing the river so as to obtain a greater navigable depth) set up new flow-characteristics causing changes in the erosive force of the stream and therefore changes in the slope of the channel. Likewise in irrigation-systems, if the various branch-channels are not properly designed with reference to slope, relation of breadth to depth, and water-discharge, serious difficulties will arise in consequence of silting and erosion, because the net of irrigation-canals seeks a condition of equilibrium defined solely by natural laws. Any attempt to prevent such a change to take place will ordinarily prove fruitless and extremely expensive because of the magnitude and persistence of the forces and energy involved.

In connection with an extensive study of the regimen of many rivers, particularly of the Missouri River and its tributaries, rivers which are extremely varied in their hydraulic and sedimentary characteristics, the writer has set up mathematical theories in an attempt to define quantitatively the natural laws governing the erosion, transportation, and deposition of alluvial materials. The mathematical derivation involves considerable space and is therefore dispensed with in this report. Instead, some of the fundamental equations are discussed together with experimental work performed to ascertain the parameters required in the application of the theory.

Water-courses differ from one another in many ways, but in general the characterizing difference is the nature of the bed of the channel and the amount and character of sedimentary material finding its way to the channel. Any rational theory of flow in such channels, therefore, must take into account the mechanical properties of the sedimentary material forming the bed. A general equation was derived by the writer taking into account the slope of the stream, roughness of the walls and bottom, character of the sediment, water-discharge, and sedimentary load. The derivation resulted in an equation of the following form for an idealized rectangular channel of infinite breadth

$$G = \psi [i^{1.4}/C^{1.2}]\, Q^{3/5} [Q^{3/5} - Q_o^{3/5}] \qquad (1)$$

where G is the quantity of sediment transported along the stream-bed in pounds per unit-width of channel, Q is the discharge per unit-width of channel (for a slope i) at which sediment-transportation begins, C is the roughness-coefficient in an open-channel-flow formula of the form $v = C R^{2/3} i^{1/2}$, and ψ is the "sediment-characteristic," an experimental coefficient depending upon the size, specific gravity, and mechanical composition of the sediment.

The foregoing equation (based essentially on the Du Boys principle) may be written in a number of other forms for use in the solution of practical problems. The equation is of general applicability but requires the experimental determination of the parameters ψ, C, and Q_o. The values of ψ and Q_o depend upon the mechanical composition (variation in size of grains as determined by sieve-analysis or elutriation), specific gravity, and form of the sediment particles, while C depends upon the character of the sediment and also the rugosities of the channel itself independent of the roughness due solely to the mechanical composition of the sediment. It is believed that once a number of experiments to determine the values of ψ, C, and Q_o have been made for a variety of sediments, the values of these parameters can be estimated with a considerable degree of precision without subjecting the materials to the hydraulic tests made in connection with this project.

The theory has been expanded mathematically to explain the equilibrium-conditions for channel-contraction works. The principle involved includes the considerations explained in the foregoing and, in addition, the fact that the sediment transported through the contracted section of the stream as well as the water-discharge, must be the same as through the uncontracted section. Contracting the stream results in greater power for erosion in the beginning but finally a state of equilibrium must be reached in which there occurs both a change in slope and change in depth of stream. Algebraically the depth in the contracted section in terms of the flow conditions in the uncontracted section, may be expressed as follows for the case of a rectangular channel

$$d = \frac{\dfrac{d_1}{(1-\alpha)^{3/7}} \left\{ -\dfrac{s_o}{w\, i_1} + \left[\left(\dfrac{s_o}{w\, i_1}\right)^2 + \dfrac{4d_1 \left(d_1 - \dfrac{s_o}{w\, i_1}\right)}{(1-\alpha)} \right]^{1/2} \right\}^{3/7}}{\left[2\left(d_1 - \dfrac{s_o}{w\, i_1}\right)\right]^{3/7}} \qquad (2)$$

where d = the water-depth at the stretch of channel which has been contracted; d_1 = the water-depth before contraction (or the depth upstream and downstream of the contracted region); s_o = the transporting force (tangential force of the water against the stream-bed per unit-area of bed) at which sediment transportation begins ($s = w, d, i$); i_1 = the natural slope of the hydraulic gradient of the stream in the uncontracted part; α = the amount of contraction, that is, $b = (1 - \alpha)\ b_1$, b and b_1 being the breadths of the channel respectively at the contracted and normal sections.

The theory has been further developed to formulate the condition of equilibrium in systems of irrigation-channels. Here ordinarily the sediment is of a very fine mechanical composition and therefore the velocity at which transportation of sediment begins is quite low in comparison to the velocity obtaining in the various canals of the system. With these considerations as a basis a special equation was developed for non-silting, non-eroding conditions. The resulting equation is of the form

$$v = [\bar{G}^{1/3}\ C^{4/3})/(Q^{1/3}\ \psi^{1/3})]\ d^{5/9} \tag{3}$$

Thus for a given network of irrigation-channels taking water from a silt-carrying stream, such as the Colorado, Missouri, or Rio Grande, the various branch-channels as well as the main canal should be so designed that the velocity

$$v = K\ d^{0.56}, \quad \text{where } K = (\bar{G}/Q\ \psi)^{1/3}\ C^{4/3} \tag{4}$$

All of the foregoing equations are based upon theoretical considerations, a number of parameters being introduced to take into account the effect of friction between sand particles and the loss of energy due to fluid friction. Essentially, therefore, this particular research project resolved itself into determining the parameters ψ, C, and s_o for particular types of sediment and also in checking these various theoretical equations when once the parameters have been numerically evaluated by experiment.

Procedure used to evaluate parameters in theory of sediment-transportation

Apparatus--The apparatus for making experiments consisted of a wooden flume one foot wide, 20 inches deep, and 30 feet long, arranged with a stilling basin at the head end, two feet by three feet in plan, and a sediment catch-basin, one foot long by three feet wide, near the discharge-end.

Sediment was added to the stream at the headwater-end of the flume and collected by means of sheet-metal catch-basins located in the reservoir one foot by three feet near the discharge-end. The rate of flow of water was regulated at the headwater-end and the rate of discharge determined by measuring the head on a rectangular weir over which the water was required to flow before entering the stilling basin at the head of the channel. After flowing through the apparatus the water returned to the sump from whence it was again pumped to the elevated reservoir supplying the pressure for flow through the system. Figure 1 presents a diagrammatical sketch of the general layout.

Materials--The materials used for these experiments consisted of two types of sand, each being used separately. In subsequent discussions these will be referred to as sand Type A, which consisted of a fine sand taken directly from the bed of a river; the other, which will be referred to as sand Type B, was a coarse material. The mechanical composition of these sands was determined by means of sieve analyses, results of which are presented in Figure 2.

Sediment-characteristics, ψ and s_o values--Suffice it to say that the sand was placed in the testing flume without a contracted section at various slopes, material being continually added at the headwater-end of the flume at such a rate to maintain the slope constant, while the rate of sediment-discharge was measured at the discharge-end of the flume for various rates of flow of water through the channel.

The final results of the investigation showing a comparison between the measured rates of sediment-transportation with the theoretical rates using the experimentally determined values of ψ and s_o are shown in Figure 3 for sand Type A.

The "critical transporting force" is not well defined for sand Type A, inasmuch as the particles are not of uniform size. Hence, a "critical" transporting force, s_o,

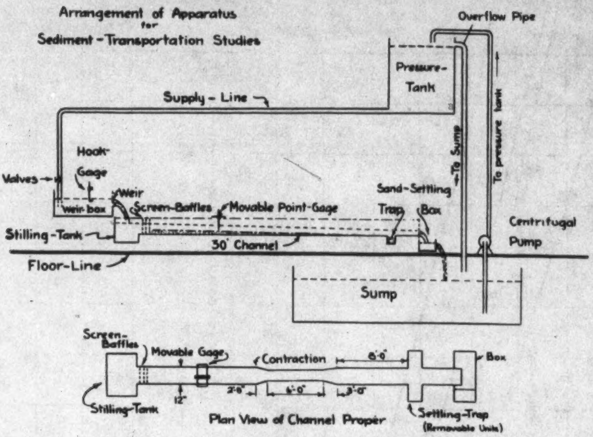
Arrangement of Apparatus for Sediment-Transportation Studies
Overflow Pipe
Pressure-Tank
Supply-Line
To Sump
To pressure tank
Hook-Gage
Valves
Weir
Weir box
Screen-Baffles
Movable Point-Gage
Sand-Settling Trap
Box
Centrifugal Pump
Stilling-Tank
30' Channel
Floor-Line
Sump
Screen-Baffles
Movable Gage
Contraction
8'-0"
Box
12"
2'-0"
6'-0"
3'-0"
Stilling-Tank
Plan View of Channel Proper
Settling-Trap (Removable Units)

Fig. 1

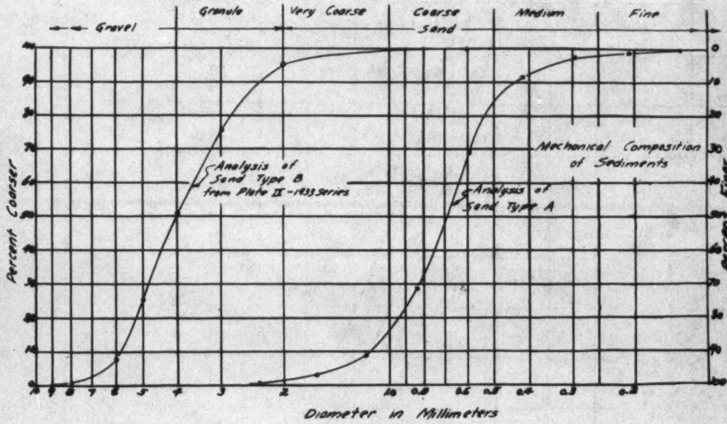

Fig. 2

is used which will best satisfy the requirements for the necessary parameter in the proposed theory.

For the two sands under consideration the characteristic values in the theory are: Sand Type A, ψ = 100,000, s_o = 0.010 pound per square foot; Sand Type B, ψ = 42,500, s_o = 0.088 pound per square foot.

The foregoing values were used in the comparison of the experimental with theoretical results in the experiments made in connection with channel-contraction works.

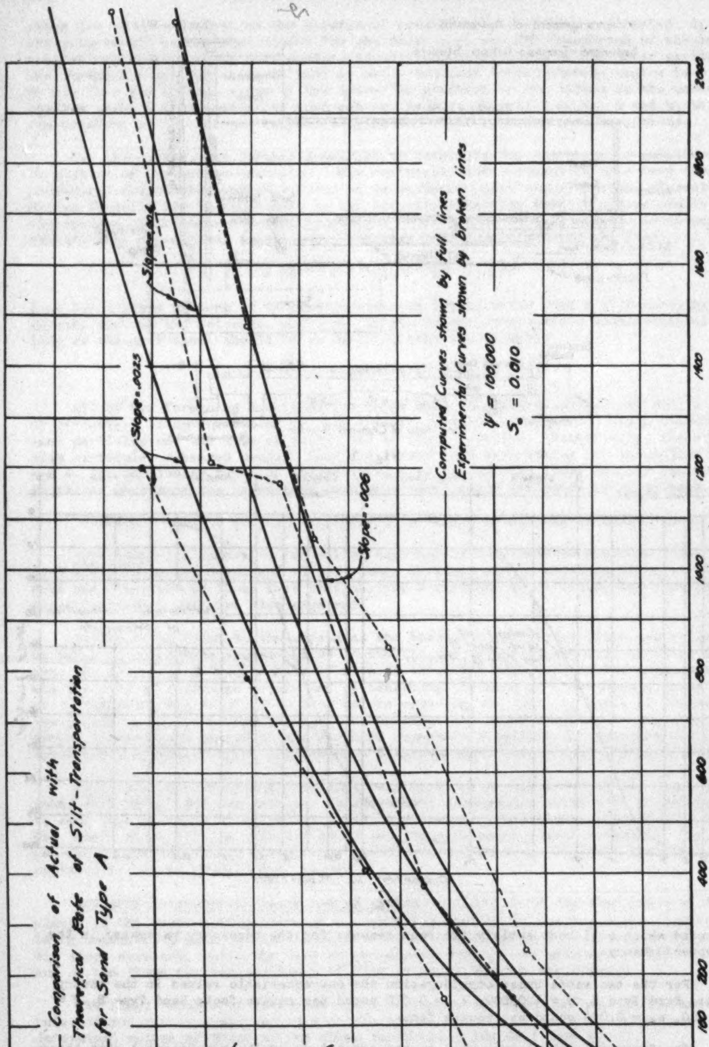

Fig. 3--Sediment Transported Lbs x 10^{-5} per sec per foot width of channel

Study of the effect of channel-contraction works

In order to verify experimentally the theory set up for the influence of channel-contraction works upon the regimen of flow in an open channel with an erosible bed, the apparatus described in the beginning of this report was arranged with a contracted section near the center of the flume in such a way that the normal breadth of one foot was maintained both upstream and downstream of the contraction works. Smooth transitions were provided both at the entrance and exit of the contraction works; the amount of the contraction amounted to 30 per cent, that is, $\alpha = 0.30$ in equation (2). The sand was placed in the channel at a definite slope and a definite rate of flow of water passed through the channel for a period of time sufficiently long to allow equilibrium to set in, that is, stability against erosion (not absence of sediment-transportation). Enough sediment was added periodically to the headwater-end of the flume to replace that transported through the channel.

Observations were made of elevation of the water-surface at one-foot intervals over the length of the channel, just prior to discontinuing flow through the flume. These were made with the aid of a point-gage which could be moved from end to end of the flume on a pair of horizontal rails. After flow was discontinued observations were made of the elevation of the stream-bottom.

The results of measurements for a number of such runs are shown in Figure 4 for sand Type A. Superimposed are the computed values by the proposed theory using the parameters ψ and s_0 which had been previously determined by other experiments. A similar comparison for the coarse sand (Type B) is shown in Figure 5.

In calculating the theoretical profile, the slope above the contracted section must be determined. In order to make the foregoing comparison of the theoretical profile with the experimental equilibrium-profile, the equilibrium-slope of the water-surface in the channel is used in the calculations. The equilibrium-slope of the water-surface was obtained by taking the average drop of water-surface through the channel. Using this slope the theoretical depth both in the normal section and the contracted section was calculated.

The agreement of the superimposed profile of the stream using the fine sand at various discharges is very satisfactory. Good flow-conditions were obtained because of the fine sediment and small discharges. The water-surface is quite regular and shows a change of slope at the contracted section. The bed of the channel at the contracted section agrees very closely with the theoretical bed-profile. In the case of the coarser sediment the profiles do not show as good agreement. The sediment particles were so large that comparatively high velocities had to be maintained in order to produce erosion. Impact upon the entrance to the contraction-works resulted in influencing the elevation of the water-surface in this vicinity so that standing waves occurred. The observations plotted for the water-surface indicate the elevations of the highest and lowest points along the water-surface. The high and low points have been connected by curved lines. Notwithstanding the difficulties arising from the very coarse material used as compared to the limited size of the apparatus, the general form of the actual and theoretical bed-profiles agree remarkably well even for the case of the coarse material.

Effect of channel-constrictions upon discharge-rating curves

Using the sedimentary characteristics of sand Type A as a basis, a theoretical analysis was made to show the effect of channel-contraction works upon the regimen of a movable bed-stream under idealized conditions. The analysis (Fig. 6) was made for a channel having a 30 per cent contraction. The conditions assumed were as follows: The channel is considered of rectangular cross-section with a relatively large breadth. The slope of the normal section (uncontracted section) considerably above and below the contracted section was assumed constant for all discharges. [This does not preclude the backwater-effect which occurs some distance upstream of the contracted section for certain discharge-conditions.]

If at the beginning of flow-conditions the slope of the channel-bottom is uniform and the discharge is progressively increased from a low value, the stage versus discharge relation at the contracted part of the channel will follow curve ABCD. No

Comparison of Theoretical
and Experimental Profiles
for Sand Type A

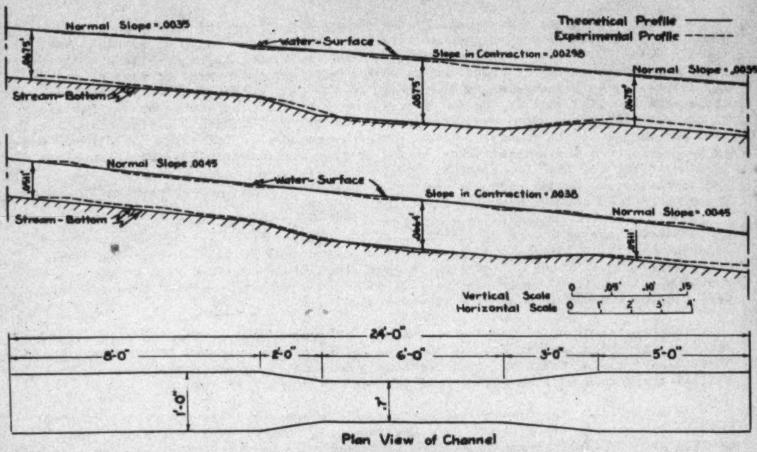
Theoretical Profile
Experimental Profile
Normal Slope = .0035
Water-Surface
Slope in Contraction = .00298
Normal Slope = .0035
.0675'
.0875'
.0675'
Stream-Bottom
Normal Slope .0045
Water-Surface
Slope in Contraction = .0038
Normal Slope = .0045
.0511'
.0464'
.0511'
Stream-Bottom
Vertical Scale 0 .05' .10' .15
Horizontal Scale 0 1' 2' 3' 4'
24'-0"
8'-0"
2'-0"
6'-0"
3'-0"
5'-0"
1'-0"
.7'
Plan View of Channel

Fig. 4

Comparison of Theoretical
and Experimental Profiles
for Sand Type B

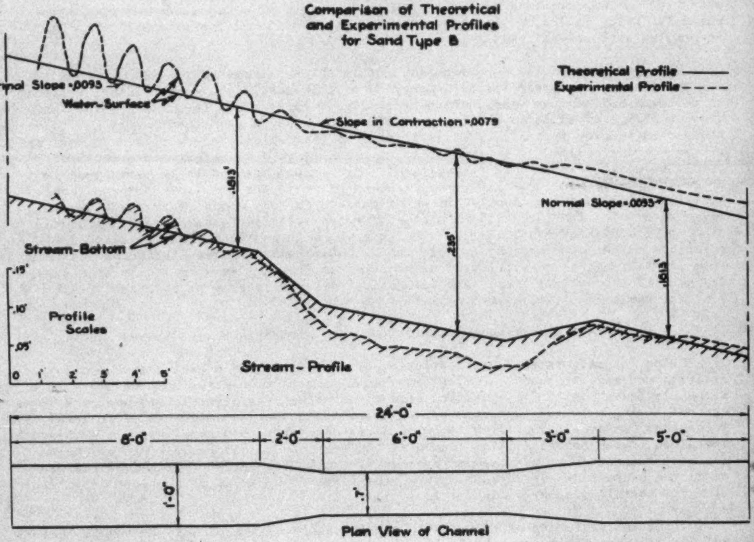
Theoretical Profile
Experimental Profile
Normal Slope = .0093
Water-Surface
Slope in Contraction = .0079
.1013'
.235'
Normal Slope = .0093
.1013'
Stream-Bottom
.15'
.10'
.05'
Profile Scales
0 1' 2' 3' 4' 5'
Stream-Profile
24'-0"
8'-0"
2'-0"
6'-0"
3'-0"
5'-0"
1'-0"
.7'
Plan View of Channel

Fig. 5

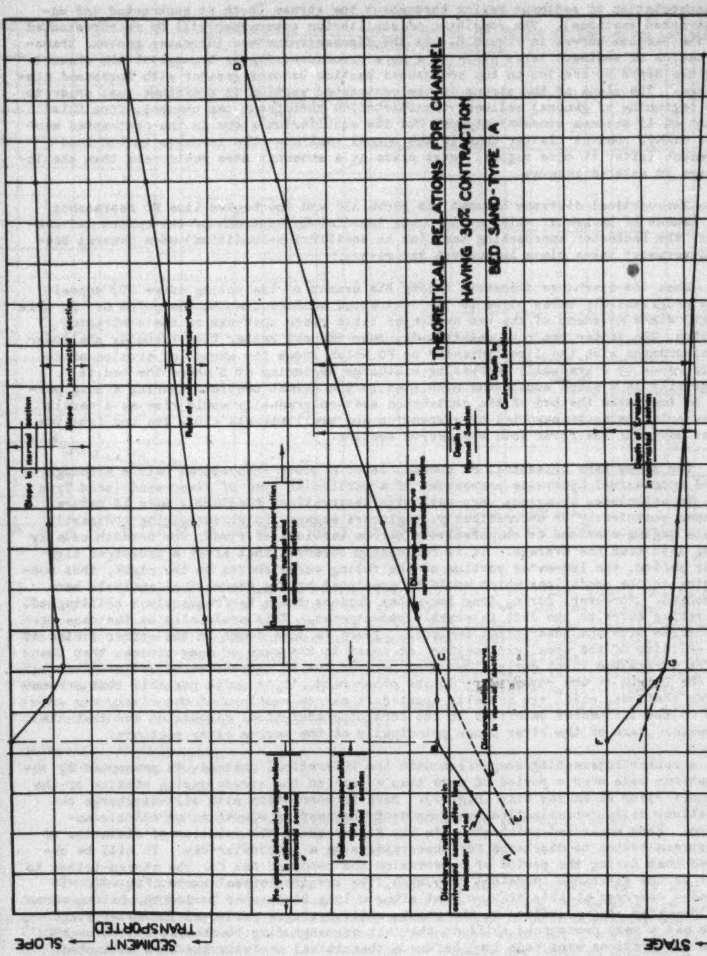

Fig. 6

sediment-transportation will occur in either the contracted or normal section provided the discharge is less than indicated at B. For a discharge in excess of that indicated at B, erosion takes place in the contracted section, the depth of erosion being indicated in the lower part of the diagram (Fig. 6). The material eroded at first causes maladjustment in the part of the stream below the contraction until finally the discharge has increased to the value indicated by C on the rating curve; at this point transportation of sediment begins throughout the stream (both at contracted and uncontracted sections). The condition of equilibrium approached will be as represented by the various curves in Figure 6. As the discharge further increases general transportation of sediment takes place to a more pronounced degree throughout the channel and the depth of erosion in the contracted section becomes greater with increased discharge. The slope of the stream in the contracted section is a minimum just prior to the beginning of general sediment-transportation throughout the channel; from this point on it becomes somewhat steeper but the equilibrium-slope in the contracted section always remains flatter than in the normal section. The increase in bed-load movement (after it once begins) takes place at a somewhat more rapid rate than the increase in water-discharge.

The vertical distance between the curve ABC and the broken line EC represents the amount of backwater which would occur immediately upstream of the contracted section, the backwater approaching zero (as an equilibrium-condition) when general bed-load movement takes place throughout the river.

When the discharge decreases (along the branch of the rating curve CD) deposition progressively takes place in the contracted section down to the point C. At this point, since movement of the bed no longer takes place upstream of the contracted section, the latter tends to maintain its deep channel rather than becoming shallower in accordance with the line indicated by FG which shows the amount of erosion which would occur by a gradually increasing discharge beginning at B where the bed is originally at a slope continuous with that in the normal section. During a long period of low water the bed of the contracted section gradually would rise as a result of material being transported by suspension and small amounts along the bed from the upper parts of the river into the narrow section.

The study here presented, of course, is of a quite theoretical nature although based upon actual hydraulic properties of a particular type of river-sand (sand Type A). Nevertheless, it agrees very well with observations frequently made in nature. Whether consciously or unconsciously, engineers engaged in stream-gaging ordinarily locate gaging-stations at comparatively narrow sections of river, the breadth usually being less than the average. It is frequently observed that after a prolonged high-water period, the low-water portion of the rating curve shifts to the right, thus conforming to the conditions which would be predicted by the theoretical analysis here presented. Moreover, during long low-water periods there is frequently a shifting of the rating curve to the left in movable bed-streams. This would also be the case in accordance with the theoretical analysis. There is some doubt in the writer's mind of the validity of the usual explanation, at least in the case of many rivers, that the entire stream-bed rises during low-water periods due to deposition of sediment throughout the length of the river-bed. On the other hand, it is quite possible that stream-gaging stations, which are normally located at narrow sections of the river, are subject to the influences described in the foregoing analytical discussion and that the low-water plane of the river drops principally at the narrow river sections.

A rather interesting comparison with the theoretical analysis is presented by observations made over a period of more than a year on the stream-gaging station of the Missouri River at Kansas City (Fig. 7). Here in connection with silt-discharge observations daily determinations were made of the average elevation of the stream-bottom. Each encircled point shown in the Figure shows the relation of elevation of the stream-bottom to discharge for observations on a particular day. It will be observed that during the period of observation the tendency was for the stream-bottom to lower as the discharge increased very much like the theoretical curve (Fig. 6). It was also observed at this station that after a long high-water period the rating curve for low-water stages shifted to the right, while during a prolonged low-water stage there was a very pronounced shift to the left corresponding to theoretical curve ABC. These observations were made long before a theoretical analysis had been attempted.

The channel in the vicinity of this gaging-station and for several miles downstream thereof at the time of these observations had a breadth of about 1200 feet, which is materially less than the breadth of the channel both upstream and downstream, these breadths being well over 1500 feet. The bed-material is not greatly different from that used in the experimental studies at the University of Minnesota. The comparison of the field-data with the theoretical analysis is therefore especially interesting.

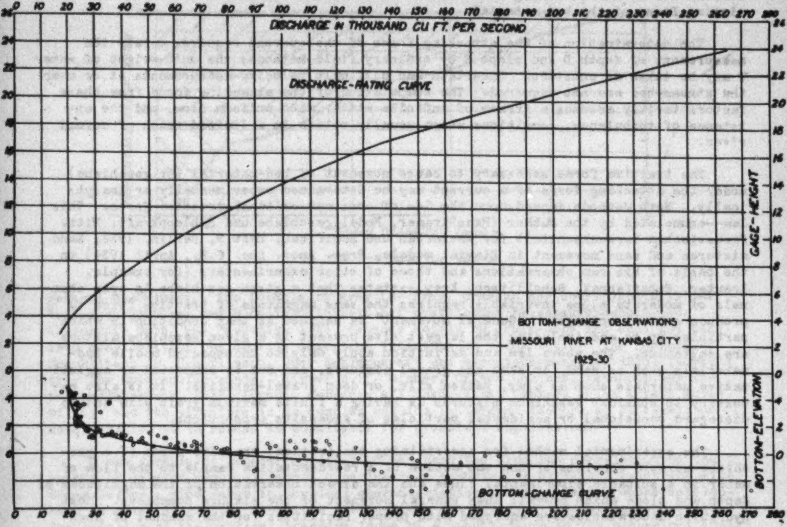

Fig. 7

In the foregoing experimental studies and theoretical analyses, conditions have been greatly idealized. The work does not go especially far into the question of the regimen of streams, not even for the case of straight channels. The time-lag effects are particularly troublesome in practical cases. The foregoing analysis takes into account only equilibrium-conditions; the duration of stages is frequently not long enough to provide equilibrium of flow or sediment-movement, thus resulting in maladjustments which cannot be readily predicted analytically. However, it is believed that the results of these studies point favorably to the possibility of experimental and analytical solutions of problems of this character.

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THE PRACTICAL APPLICATION OF THE DU BOYS TRACTIVE-FORCE THEORY

Hans Kramer

Because of awakened realization of its simplicity and rationality, the du Boys concept of the action of tractive force of the current in moving bed-material (or geschiebe) in an open channel is coming into extensive use in both laboratory and field-studies of practical river hydraulics. The du Boys equation, $T = \gamma DS$ (P. du Boys, Le Rhône et les Rivières a Lit affouillable, Annales des Ponts et Chaussées, 1879, II), expresses the dragging, entraining, or tractive force T exerted at its base by a prism of water of unit cross-sectional area and height D sliding under the influence of gravity down an inclined plane having a slope S; or in more scientific language, it expresses the unit shearing-force in a wide channel of depth D at zero distance above the bottom.

The practical application of the du Boys theory involves two steps: (1) The determination of the attacking force of the current; (2) the determination of the resisting force of the bed-material.

The determination of the attacking force of the current requires merely the measurement of depth D and slope S by ordinary field-methods; the unit-weight of water γ may be taken as constant. Uncertain and difficult velocity-measurements at or near the stream-bed are not required. The computation of the attacking force from these factors tacitly assumes a stream of infinite width, with uniform flow, and the existence of turbulence, conditions which usually obtain in a limited reach of normal river.

The tractive force necessary to cause movement of bed-material (or geschiebe) under the attacking force of a current may be determined experimentally or analytically. Both methods depend upon the law of constant critical tractive force. This law--enunciated by the author (Hans Kramer, Modellgeschiebe und Schleppkraft, Mitt. Preussischen Versuchsanstalt für Wasserbau und Schiffbau, Heft 9, Berlin, 1932; Sand mixtures and sand movement in fluvial models, Proc. Amer. Soc. C.E., April 1934) on the basis of his own observations and those of other experimenters (for example, Kreuter, Schaffernak, Schoklitsch, Krey)--states that a given geschiebe in open channels of moderate slope invariably requires the same magnitude of tractive force to produce general movement. "General movement" is defined as that condition in which particles up to and including the largest size present in a given geschiebe mixture are saltating. The above law and definition apply only to uncompacted mobile bed-materials such as sand, or sand and gravel mixtures, and not to compacted or agglutinative materials such as clay, packed silt, or deep gravel-deposits. It is also necessary to consider geschiebe mixtures as having a finite maximum grain size and to disregard occasional or accidental particles of excessive proportions.

The experimental method for ascertaining the critical tractive force of a geschiebe mixture consists of the subjection of a representative sample to the flow of water in a suitable experimental flume and the direct observation of the magnitudes of depth and slope which prevail when general movement of the mixture commences. Most hydraulic laboratories are equipped with proper facilities for the conduct of such tests. For major projects it may be desirable to improvise a simple testing flume at the site of the work. The test-data obtained by a qualified observer may contain errors arising from his subjective judgment but will usually possess a degree of accuracy commensurate with that of allied stream-data. MacDougall (C. H. MacDougall, Bed-sediment transportation in open channels, Trans. Fourteenth Annual Meeting, Amer. Geophys. Union, p. 494) has suggested an improved method to eliminate the source of personal error.

The analytical method for computing the critical tractive force T_o of a geschiebe mixture consists of the application of a mathematical formula to its physical properties. The determining factors for such a formula may be written as follows: $T_o = f$ (grain-size, grain-distribution, grain-form, denseness, texture, unit-weight). Of these, grain-size and distribution are determinable by the usual sifting processes, the resulting mechanical analysis being depicted as the gradation-curve of the mixture. The geometric shape of individual sand-grains may be obtained from laborious measurements but, for most practical purposes, the common types of river-sand can be considered to be of similar geometric form; the form-factor can thus be eliminated as a separate variable. The voids ratio of a mixture is an index of its denseness; though capable of direct measurement, the voids ratio is also reflected by the character of the gradation-curve. The texture-factor must be omitted from consideration since its effect cannot be evaluated; to a certain extent, however, the effect of texture is already embraced in the grain-size, grain-distribution, and denseness-factors. Unit-weight is, of course, readily determinable. With the foregoing simplifications, the general expression for a mixture's critical resistance to movement in terms of its physical properties may be reduced to

$$T_o = f\ (d)\ (e)\ (\gamma_1 - \gamma) \tag{1}$$

where d is grain-diameter, e is the voids ratio, and $(\gamma_1 - \gamma)$ is the effective density.

Several European experimenters have developed specific forms for equation (1) but, without exception, these special formulas possess inherent defects which vitiate their

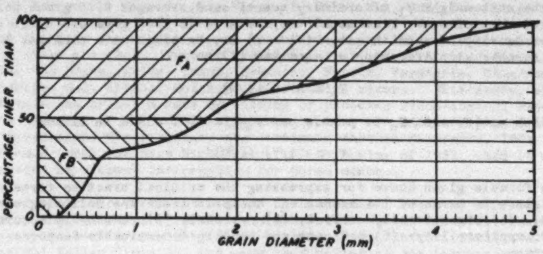

FIG. 1—GRADATION-CURVE

general usefulness. The formula of Krey (H. Krey, Grenzen der Übertragbarkeit der Versuchsergebnisse und Modellähnlichkeit bei praktischen Flussbauversuchen, Zs. angewandte Math. und Mechanik, 1925) depends solely on grain-size and does not take into consideration the equally important influence of voids ratio. The formula of Schoklitsch (A. Schoklitsch, Über Schleppkraft und Geschiebebewegung, 1914) is valid only for unigranular sands. Eisner's (F. Eisner, Offene Gerinne, Handbuch der Experimentalphysik, 1932) formula embraces all theoretical factors which affect movability, but its structure is so complex and its individual factors so difficult of determination as to render it unsuitable for practical application.

A new formula of broader application has resulted from the correlation by the author of data of seven different experimenters covering 24 different geschiebe mixtures having a wide range in physical characteristics. This formula, whose development is given in greater detail in publications previously cited, states the following relation of the critical tractive force of a sand-mixture to its mechanical analysis

$$T_o = (100/6)\ (d/M)\ (\gamma_1 - \gamma) \qquad (2)$$

where T_o, as previously defined, is the critical tractive force of the mixture in grams per square meter, $(\gamma_1 - \gamma)$ is its effective density in grams per cubic centimeter, and, as defined below, d is the mean grain-diameter in millimeters, and M the modulus of uniformity, both determined from the gradation of the mixture. Equation (2) takes into account the important experimental fact, not heretofore expressed by formula, that a mixture's resistance to movement in addition to varying directly with grain-size also varies inversely with voids ratio.

The factors d and M of equation (2) are evaluated by reference to Figure 1, which depicts an arithmetical (not semi-logarithmic) plot of an assumed gradation-curve. The uniformity modulus, M, is the ratio of the area below the 50 per cent abscissa, F_B, to the area above the 50 per cent abscissa, F_A. Thus $M = F_B/F_A$ is a modulus of the deviation of the gradation-curve from the vertical of uniform grain-size which, in turn, is a measure of the voids ratio of the mixture. The mean grain-diameter, d, is the mean abscissa of the gradation-curve (it is to be noted that the mean grain-diameter thus determined is not necessarily equal to the median grain-diameter determined by the intercept of the 50 per cent abscissa on the gradation-curve). The evaluation of M and d does not depend upon any particular choice of scale; their values may be computed directly from the sieve-analysis data without resort to plotting and planimetering the gradation-curve.

In view of the character and scope of the scattered data from which equation (2) was derived, it is necessary to limit the probable accuracy and the present field of application of the formula. Critical valuation of the basic data indicates a probable accuracy within ± 15 per cent, a range which is generally admissible. Limits of application are for quartz-sand mixtures, including gradations of moderate abnormality, containing grains not larger than five millimeters and having a critical tractive force not exceeding 80 grams per square meter; these limits embrace most laboratory mixtures and many varieties of natural geschiebe.

Since the unit-weight γ_1 of ordinary quartz sand averages 2.65 grams per cubic centimeter and that of water γ at usual temperatures is 1.00 gram per cubic centimeter, the effective density of sand in water $(\gamma_1 - \gamma)$ may be taken as a constant 1.65; this permits the further simplification of equation (2) to

$$T_o = 27.5\ (d/M) \tag{3}$$

or, for English units, with T_o in pounds per square foot and d in inches

$$T_o = (1/7)\ (d/M) \tag{4}$$

The new formula given above for expressing the critical tractive force of a geschiebe mixture in terms of its mechanical analysis meets the following essential requirements: (1) Dimensionally correct; (2) rational; (3) reasonably accurate; (4) fair range of applicability; (5) definite and readily determinable factors; and (6) simple structure.

With active research in this field now in progress at the United States Waterways Experiment Station, the Bureau of Standards, and other hydraulic laboratories, it is altogether likely that improvements in accuracy and applicability of the basic formula herein presented will be developed.

U. S. Engineer Office,
Memphis, Tennessee, April 1934

SEDIMENT-STUDIES AT THE UNITED STATES WATERWAYS EXPERIMENT STATION

Herbert D. Vogel

Problems of river-regulation and river-control are seldom concerned solely with the dynamics of fluid flow, for in nearly every case there must also be considered the cause and effects of movement by the stream of enormous quantities of bank and bed material. The full appreciation of this problem of sediment-movement must be based not only upon an intimate study and analysis of the laws which control the erosion of solid materials by flowing water but also upon a consideration of the several methods of transportation, including hydraulic traction, suspension, and solution. Cognizance of the volume as well as the manner of transportation is of definite importance. These data may be acquired only by combined field and laboratory investigations.

Every alluvial river in its course of flow is continually picking up earthy materials and, by way of exchange, depositing a part of the load which it is already carrying. This action is evidenced in bank-caving and bar-building phenomena. In addition to that material which is in almost continuous contact with the bed (designated "bed-load" or "geschiebe"), a certain amount of sediment, in its finer state of comminution, is carried in suspension, while substances of a soluble nature are transported in solution.

To the end of learning more about the fundamental or basic laws controlling the transportation of sediment by the Mississippi River, the United States Waterways Experiment Station, since 1929, has carried on an almost continuous program of field investigations, supplemented by laboratory analyses. The geographical scope of these researches extends from the confluence of the Missouri River and Mississippi River to the mouth of the latter at the Gulf of Mexico. In addition to studies on the Mississippi, comprehensive observations have been made on most of its major tributaries.

The first published results of this study of suspended sediment in the Mississippi were contained in a paper entitled "Sediment-investigations on the Mississippi River and its tributaries prior to 1930" (Paper H), the first printed report of the United States Waterways Experiment Station, prepared in December, 1930. This paper presented a review of all previous investigations of material in suspension in the Lower Mississippi, together with descriptions of the various methods used in obtaining and analyzing the samples.

In the early fall of 1930, ten sediment-observation stations were established at selected locations on the Mississippi, Missouri, Ohio, Old, and Atchafalaya rivers, the purpose being to collect additional data on the amounts of sediment carried in suspension by the main stream, its upper tributaries, and its outlets, under varying conditions of stage and flow. Sixteen additional stations were located on tributaries, including the Black, White, Yazoo, Arkansas, Neosho, Verdigris, Cimarron, South Canadian, Washita, Red, Little, Sulphur, and Ouachita rivers. This study, which was made to ascertain the probable rate of silting of proposed flood-control reservoirs and to add to the fund of data concerning the movement of sedimentary materials through the Mississippi River system, was continued through September, 1931. It was then discontinued until the next high water, in the spring of 1932, when it was resumed and carried on without interruption for three months.

Samples of water were taken at each of these stations from the surface, at mid-depth, and near the bottom, at from five to ten points on the traverse observation-range. All samples were procured by field-parties of the three districts within the Lower Mississippi Valley Division, and were then mailed to the Laboratory for analysis. Details of procurement and analysis, together with complete results of all but the investigation of the last three months, are contained in the report "Sediment-investigations on the Mississippi River and its tributaries 1930-31" (Paper U) of the United States Waterways Experiment Station. Results of the high-water investigation will probably be printed this year.

Following the investigations of 1930-31, which constitute the most comprehensive series of suspended-load studies ever made on the Mississippi system, an almost equally ambitious program was undertaken to determine the characteristics of the material composing the bed of the Mississippi. More than 500 small samples were taken from the bed of the stream between Cairo and New Orleans, and about 150 additional samples were taken from the tributaries and outlets, including the Ohio, Red, Black, Old, and Atchafalaya rivers. These samples were sent to the United States Waterways Experiment Station, where they were subjected to mechanical analyses and microscopic examinations to determine the size, distribution, shape, and composition of the materials. After completion of the tests at the Station, each sample was divided and half of each was sent to the Geology Department of the Louisiana State University for a petrographic examination. This latter study had for its purpose the determination of the mineralogic constituents of the material, with the ultimate objective of determining the source and rate of downstream progression of the materials.

At several points in the river, larger samples were procured by dredges. These samples, after being subjected to the routine mechanical and microscopic examinations, were tested in the tilting flume at the Station in an effort to find a relation between the physical properties of the materials and the tractive forces required for their transportation. These latter determinations are of practical value in two ways: (1) They supply data which may contribute to a knowledge of the resistance to movement of the bed of the Mississippi; and (2) they supply information needed for the design and operation of river-models. By means of the development of a mathematical expression relating tractive force and bed-movement, it may become possible to determine from the results of a mechanical analysis of a given bed-material the depths and slopes required for its various rates of movement. River-models then can be designed to employ any particular sand, with assurance that conditions of movement will be in consonance with those in the natural river.

About 675 bed-samples have already been subjected to laboratory tests, and plans are being matured for an extension of the investigation to include tributaries of the main river. Close cooperation between field and laboratory personnel is serving to obtain data which show the distribution of suspended solid particles in a vertical section of the river, and which further reveal the manner in which percentages of solids increase toward the bottom, where movement is wholly by traction. A paper covering the results of the entire investigation, except those of the petrographic survey, will be released in May or June 1934.

The Soils Mechanics Laboratory of this Station, which has recently been improved, is performing tests to determine the physical properties and characteristics of soils, both in the disturbed and the undisturbed state, and of those soils carried in suspension by streams. The studies and tests of soils in the disturbed and undisturbed states pertain to their use as an engineering material, especially in levee or earth-dam construction. The studies of transportation by streams of soils in suspension are prosecuted for the purpose of aiding in the development of plans for flood-control, harbor-improvement, navigation, etc.

The classification of soils under the general heading of sand, silt, and clay is accomplished by the mechanical analysis, both the sieve- and hydrometer-methods, the Atterberg Limits, and microscopic examination. Tests, such as absolute and mass specific gravity and water-content, are performed to supply general factual information. The determination of the extent to which a soil has been consolidated in its undisburbed state, and the effect of changes resulting from increased loading, may be achieved by the consolidation or compression-test. The variation in the permeability of soil with respect to its state of consolidation may also be determined directly during the compression-test.

The information gained from the analysis and study of the soils is used in estimating the rate and amount of settlement or subsidence of structures, such as levees or earthen dams, the stability of the structures during the construction-period, and their ability to impound water.

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RECORDS OF SILT CARRIED BY THE RIO GRANDE AND ITS ACCUMULATION IN ELEPHANT BUTTE RESERVOIR

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The encroachment by accumulated silt-deposit upon the storage-capacity of any reservoir having a silt-bearing stream as its source of supply is a serious problem. It is one of particularly grave concern in the arid southwest. Of the principal streams in the southwest the Rio Grande probably carries the highest silt-burden, both in the matter of absolute maximum percentage of silt-load to discharge reached during any particular flood and the average ratio of the total amount of silt transported to the total discharge of the stream. These percentages are approximately twice the corresponding ratios for the Colorado River. Silt in the flow of the Rio Grande has been under observation and records of the amount carried are available for a longer continuous period than for any other southwest stream.

If the silt in the Colorado River has attracted more attention or has caused more concern, it is because of the total quantities involved being approximately in the once familiar ratio of 16 to 1. The mean total annual discharge of the Rio Grande into Elephant Butte Reservoir is about 1,100,000 acre-feet, while that of the Colorado is about 16,200,000 acre-feet at Yuma.

For 20 years now too, the major portion of the silt carried by the Rio Grande has been depositing and accumulating in Elephant Butte Reservoir which was constructed with an original capacity of 2,638,000 acre-feet, about two and a half times the mean annual discharge of the Rio Grande. The Reservoir was planned with this large surplus capacity for the dual purpose of regulating the entire flow of the Rio Grande, carrying water accumulated in years of abnormal runoff over for irrigation-use during years of drought or below normal runoff, and to allow for the accumulated deposit of silt over a long period of years. The major silt-problem of the Rio Grande has then for these many years escaped the attention of the people on the Rio Grande Project, except of those who realize its full import and ultimate results and so are concerned about it. This is quite a different situation than would be if the silt was still being deposited over the valley by flood-overflows or carried onto the land by the irrigation-water and creating an annoying and expensive irrigation-canal silting and cleaning problem.

I know of no more concise and effective way of describing the Rio Grande in a general way than to quote from Mr. W. W. Follett's publication "Silt in the Rio Grande," calling attention, of course, to the modifications that have been brought about by the construction of Elephant Butte Reservoir, and stating here that my remarks are to be confined to that portion of the Rio Grande north of El Paso and more particularly above Elephant Butte Reservoir:

"The Rio Grande is some 1500 miles long, measured along its axis and not counting sinuosities in alluvial valleys. Near its source in Colorado and northern New Mexico, its waters are limpid, carrying practically no sediment in suspension, and are filled with mountain trout. The Chama furnishes the first silt, and this only when some of its southern tributaries are in flood. Sometimes the Jemez and frequently the Galisteo deliver silt, so that at Albuquerque the river is sometimes quite muddy.

"The principal sources of silt are the Puerco and the Salado. These are torrential streams of great declivity and, when in flood, bring down large quantities of mud, a part of which, upon the slackening of the current by the flatter slope of the Rio Grande, is dropped and then later on is gradually picked up by the clear waters from the upper river, and so is slowly carried downstream. Both these streams enter the Rio Grande between Albuquerque and Socorro, and frequently deliver torrential floods during the summer and fall. For weeks after one of these floods the water of the main river will be loaded with silt as far down as the mouth of the Conchos. Even the snow-waters of spring, which are practically clear when they start on their journey to the Gulf, pick up, in their passage through the alluvial valleys between Albuquerque and the Conchos, considerable silt from caving banks and the remains of previous summer Puerco floods. The Conchos' clearer water dilutes the muddy flow from above and it is further diluted by the flow of the Pecos and Devil's rivers and of the springs in the Canon.

"Thus the whole Rio Grande may be divided, as regards its carrying of silt in suspension, into three divisions. From its source to Albuquerque, 300 miles, the water is practically clear. From there to the mouth of the Conchos, 500 miles, the water is muddy and is sometimes saturated with silt; that is, is carrying all it possibly can at the rate at which it is moving. From the Conchos to the Gulf of Mexico, 700 miles, it is a silt-bearing stream, but the average per cent of silt is much less than in the middle section."

As you see, Mr. Follett has divided the whole of the Rio Grande Drainage-Basin into three divisions as regards its carrying of silt. As regards the source of the silt, the drainage-area above Elephant Butte Reservoir can be divided into two principal sections: (1) The mountainous more or less timbered area in south-central Colorado and north-central New Mexico, with an area of 11,028 square miles not including 2900 square miles in the enclosed portion of the San Luis Valley, with no visible outflow; and (2) the broken, generally barren area in central New Mexico, having an area of 13,621 square miles extending from near Santa Fe (Buckman gaging-station) to San Marcial at the head of Elephant Butte Reservoir.

The discharge of the Rio Grande above Elephant Butte Reservoir may also be divided into three classifications: (1) The increased flow of the late spring floods originating from the melting snows of the mountain areas; (2) the flashy torrential floods of summer and early fall originating from rains which may be more or less general or from local storms approximating cloud-burst proportions falling on the central New Mexico area; and finally (3) the normal flow during other portions of the year.

The seasonal discharges of the Rio Grande are cyclic and fluctuating with no regularity of frequency or flow. The spring runoff from melting snow which is normally relied upon to replenish the stored water in the Reservoir ordinarily occurs over a period of from two to six weeks some time during the month of April, May, or June. The discharge usually attains stages of from 6000 to 10,000 or 12,000 second-feet, but has reached peaks at high as 20,000 second-feet, or more, while in other years, about one out of six, it has not exceeded 3000 second-feet. During the summer months after the snow-runoff has subsided the River at San Marcial is usually dry or nearly so, except for the short flashy and occasional torrential runoff from summer rains. Flows from summer rains are of varying frequency, high discharges occurring only about one year in three, and some years pass without any unusual summer floods. However, on two occasions during the past 40 years of record they have reached maximum record flood-stages. For October 11, 1904, a mean daily discharge of 33,000 second-feet is recorded and for September 24, 1929, 29,000 second-feet with a possible peak then of 48,000 second-feet. During the fall and winter months the discharge ranges from no flow to 1000 second-feet, depending on conditions over the watershed. The normal flow of early spring and summer is practically all utilized for irrigation in the upper Rio Grande valleys in Colorado and New Mexico and on the tributaries.

Practically all of the silt-burden of the stream is carried in by the summer floods from the generally barren, broken central New Mexico portion of the Drainage-Basin through tributaries that are ordinarily dry. The writer has had no opportunity to make a personal investigation nor has he had occasion to make an intensive study of the method of erosion which produces the silt-burden; that is, whether it is surface-erosion, gully-erosion, or otherwise. From casual observation he is of the opinion that a very large portion of the silt-burden is the result of the caving of the steep and high banks along the larger drainage-courses as they are undercut by the torrential discharge of the streams when the main current meanders from one side of the channel to the other.

The silt-burden of a stream may be determined usually by one of two methods: (1) The collection of silt-water samples and their analyses to determine the relative amount of silt being transported; and (2) the other method is the conducting of silt-surveys in reservoirs where the silt-deposits have accumulated. The first method is productive of more or less approximate results only for the reason that conversions must be made, which are in turn based upon certain assumptions. First, after a silt-water sample has been taken it can not be stated to what degree it is representative of the total silt-burden of the stream. It is only reasonable to assume that a certain per cent of the total load moves along the bottom of the stream and may not be accounted for in the sample. Second, considerable depends upon the frequency of collecting samples. Then because it is impracticable to obtain from the samples a direct volume-relation for the silt when deposited in place in a reservoir, the determination is first made from the samples in terms of ratio or percentage by weight of silt to water. For practical use this then requires a conversion to volume, for which purpose there must be known or assumed the net dry weight of a given volume of silt as deposited in place under the conditions pertaining to the problem in mind for which the determinations are being made; that is, if for determining the encroachment upon a reservoir-capacity we must have a value for the net dry weight of the silt in a given volume when deposited and consolidated in the reservoir area. The determination of the net weight of a given volume of silt for use in these determinations has proven to be a much more difficult task than would appear on the surface.

Values for the net dry weight of a cubic foot of deposited silt have been determined or assumed for use in the computations of the volume of silt carried by the Rio Grande ranging all the way from 50 to 100 pounds. A value of 53 pounds per cubic foot was used by Mr. Follett as obtained from a determination made jointly by himself and Engineer B. M. Hall when the first report was made on Elephant Butte Storage-Reservoir and from a single three-inch cube cut from a silt-bar on the Rio Grande near El Paso. The mean of many other determinations from samples of larger but varying volumes and by several different persons gives a result approximating about 90 pounds per cubic foot. Most of these determinations, however, were also made on silt taken from bars along the River at various locations between San Marcial and El Paso. No determinations have yet been made from individual or composite samples of deposited silt as it has actually accumulated in the bed of Elephant Butte Reservoir. This still presents an interesting problem which may yet be undertaken along with the chemical, physical, and mineralogical analyses of the silt.

The weight of 53 pounds per cubic foot of dry silt is being used for conversion of the data obtained from silt-water samples taken at San Marcial to determine the amount of silt entering Elephant Butte Reservoir during the periods between reservoir silt-surveys. It is being used because the results obtained by its application have checked almost exactly the results obtained by actual reservoir silt-surveys. It is being used, however, with the conviction that it is probably lower than the actual dry weight of a cubic foot of deposited silt, but also with the belief that silt-water samples obtained from the Rio Grande discharge at San Marcial do not represent the total silt-load transported; that the actual per cent of silt carried is somewhat greater than determined from silt-water samples because of the probable increased load carried along the bed of the stream. If these conditions are as surmised they constitute compensating errors and give a result which checks with those obtained by the more reliable method of conducting actual reservoir silt-surveys.

Deductions made from the taking of silt-water samples of the stream-discharge serve two important purposes or uses in connection with the study of storage-reservoir investigations and operation. They form the only basis for predicting the probable useful life of a proposed storage-reservoir, and they can be used in connection with the actual operation of a storage-reservoir for observing the approximate amount of silt entering the reservoir and consequent progressive encroachment upon the storage-capacity during periods between actual reservoir silt-surveys.

The volume of accumulated silt-deposits in a reservoir may be determined by actual reservoir silt-surveys with any degree of accuracy to which it is economically practical to conduct the silt-surveys and to which the original reservoir-surveys were run. The usual method is to redetermine the elevations from time to time over established cross-sections located approximately at right-angles to the axis of the reservoir. Plane-table topography or ordinary profile-survey means may be employed over the exposed portions of the reservoir-area but sounding and triangulation methods must be resorted to over the submerged portions. The volume of the silt deposited in the reservoir may then be computed by using the vertical cross-section area of silt deposited on adjacent sections as end areas in the usual prismoidal formula. The main value of a silt-survey, however, is not obtained if a revised elevation versus capacity table or curve can not be prepared from the results of the survey. To accomplish this the amount of silt deposited between adjacent horizontal planes at established contour-elevations must be computed and deducted from the original volume-increments of the reservoir-capacity table between those contour-elevations; or the remaining volume of the reservoir may be computed direct by using the reestablished area of each contour plane as reduced by the silt-deposits encroachment.

Silt-water samples have been taken and determinations made therefrom for the amount of silt carried by the Rio Grande with somewhat varying frequency but almost continuously since storage on the River above El Paso was first considered, except for a year or two when there was no gage-reader employed at the stations. Such sampling was begun at El Paso in June 1889, and it continued intensively to August 1890. Beginning again in May 1897, occasional samples with increased frequency during floods were taken until August 1905, and beginning on that date systematic frequent sampling, at three-day intervals, was carried on until June 1910. Systematic sampling at San Marcial was begun in August 1905, and continued at three-day intervals until September 1921, and then with varying frequency to date, with the exception of the year 1923 when no gage-observer was employed at the station. Silt-water samples are now being collected at San Marcial regularly once a week with increased frequency during flood-discharges.

The silt-load carried by the discharge of the Rio Grande depends upon the character of the runoff and its source. The flashy summer floods from the broken and generally barren drainage-area in central New Mexico usually carry from four to ten per cent but occasionally it has reached as high as 12 to 15 per cent by weight of silt, characterized by its high percentage of colloidal argillaceous or clay matter, while the spring runoff from melting snows which normally produces the bulk of the total annual discharge carries only about one-half of one per cent or less of silt. The discharge from the snow-runoff originating in the mountainous, more or less timbered, areas of the upper protion of the Drainage-Basin, in south-central Colorado and north-central New Mexico, enter the stream, and would pass on, as practically clear water if it were not for the silt deposited in the Valley and along the River channel through central New Mexico by the summer floods of previous seasons, some of which is picked up from channel-scour and bank-erosion to be retransported as the spring floods pass down the river.

Since the beginning of storage-operation in Elephant Butte Reservoir in 1915 the entire flow or discharge of the Rio Grande entering the Reservoir has been retained in it until released under full control and regulation to meet irrigation-requirements, there having been no spill from the Reservoir, and it might be added no shortage in the water-supply, during the 20 years of operation. All of the silt carried by the Rio Grande entering the Reservoir has been deposited and accumulated within the reservoir-area except occasionally during brief periods when silt-flows have been discharged through the Reservoir.

Two reservoir silt-surveys have been conducted, one in 1920 and another in 1925. The results obtained from these surveys indicate that the average amount of silt transported by the Rio Grande into the Reservoir has been 1.66 per cent by volume of the total inflow entering the Reservoir at San Marcial, and that the mean average amount of silt entering the Reservoir annually is approximately 20,000 acre-feet. The result of these surveys and the computations based on silt-water samples for the period since the last silt-survey to date indicates that a total of 367,598 acre-feet of silt have entered the Reservoir and practically all of it has been retained in the accumulated silt deposits within the reservoir-area. The proportions of these volumes can be more readily appreciated when it is realized that if deposited over the entire irrigated area in the valleys below Elephant Butte Reservoir it would elevate the land about two feet.

Where the silt that has deposited in the Reservoir and is accumulated there would now be, had it not been for Elephant Butte Reservoir, will remain a matter for some speculation. Some of it, of course, would have travelled down the River beyond the irrigation-project. However, it is not probable that the entire or even equivalent amount would have passed beyond the valleys; undoubtedly a large portion of it would have been deposited over the valley-floor as it would have been inundated by the floods. Some of the silt-load that would have been deposited on the valley-floor would, of course, have been replaced in the river-discharge as it left the valleys by channel erosion but probably not an equivalent amount. Some of the silt would have been carried over cultivated land by irrigation-water and some settling in canals would be thrown up in ditch banks by successive cleanings.

An interesting and very striking phenomenon, at least from scientific consideration, has been the occasional flow of silt through the Reservoir for short periods following the entrance of heavily silt-laden floods into the upper end of the Reservoir. When the heavily silt-laden summer floods originating in the central portion of New Mexico enter the Reservoir and irrigation-water is being released from the Reservoir at the lower end, the silt-laden water has moved along the bottom of the Reservoir and discharged through the outlet-gates without being in evidence to the slightest degree on the surface of the lake. Such flows have now occurred in seven years out of 20-years' operation of the Reservoir, and each time the head of the lake was between 30 and 40 miles above the dam.

Observations have revealed that the silt-laden water flows along the bottom of the lake in a very thin sheet (less than 5-foot depth), or through the lowest portions of the floor of the Reservoir much as water itself flows under air, and apparently does this without diffusing into the water already in the lake, as it retains certain distinct characteristics which are evident and have been observed as it is discharged from the outlets. There may occur some modifications of these characteristics of the silt-laden water during its passage through the Reservoir, but it even retains a temperature higher than that of Reservoir water as it flows along beneath the clear water. When the silt-laden water is being discharged from the outlet-gates it carries a silt-load up to 6 per cent by weight. The temperature of the outflow immediately rises about 6° and the soluble salt-content increases materially. With the clearing up of the outflow-water which usually occurs quite rapidly the temperature of the outflow drops back to the normal temperature of the Reservoir outflow for that particular season of the year and the soluble salt-content also drops off to that of the ordinary Reservoir water. The character of the silt in the Reservoir discharge is almost pure finely divided clay with all particles of grit or heavier silts completely removed, these having been deposited within the Reservoir area.

The conditions productive of a silt-flow through the Reservoir may be observed to be as follows: They occur when heavily silt-laden floods, usually carrying from four per cent to ten per cent of silt by weight, originating from rains on the Rio Grande watershed in central New Mexico enter the Reservoir. The silty outflows, carrying from two per cent to six per cent of silt, usually continue for only a few days, the duration depending upon the volume and duration of the flood-inflow and the quantity being released from the Reservoir. With the head-waters of the lake between 30 and 35 miles above the dam the silty water makes its appearance in the outflow in from two to five days after entering the Reservoir. The silt-load in the outflow reaches its maximum quite rapidly and clears up at the end of the run with equal dispatch. No observations have been made to determine the depth to which the silt-laden water accumulates just above the dam but it is planned to make such a determination.

The reason for this phenomenon has caused some wonderment but it is undoubtedly explained by the fact that the silt-laden water as it is discharged from the Reservoir weighs up to two or three pounds more per cubic foot than clear water. Its flow along the bottom of the lake is, therefore, undoubtedly explained by its higher specific gravity, but why it does not diffuse or mix more than it does with the Reservoir water and why it retains its own particular characteristics, including a higher temperature, may be a matter for further scientific analysis.

Its economic significance is of somewhat doubtful importance. The total volume of the silt passing through the Reservoir with these flows is so relatively small compared to the total volume of silt entering the Reservoir and being deposited there that it is of little consequence in prolonging the useful life of the Reservoir. The total volume carried through the Reservoir in this manner to date is estimated to be only about 5000 acre-feet. As the storage-capacity of the Reservoir is more and more encroached upon by accumulated silt-deposits, silt-flows through the Reservoir may be expected with progressively increasing frequency and duration.

The value of the silt being discharged through the Reservoir is distinctly negative from an agricultural and irrigation project-operation viewpoint. It is deposited in the canals and laterals of the irrigation-distribution system and has a very material effect upon decreasing water-carrying capacity and increasing the difficulties and costs of cleaning. Farmers hesitate to use the water for irrigation and ofttimes prefer to wait until the water clears up rather than use the muddy water when it is thickest. The clay-silt of these flows is not considered to have any fertilizing value and when deposited it forms a heavy obdurate and impervious soil. If used for irrigating young plants or newly-sown alfalfa it kills the plants or young shoots.

Peculiarly enough this is somewhat contrary to the situation and sentiment often expressed about the time Elephant Butte Reservoir was put into operation, or just previous thereto, when expressions were frequently heard bemoaning the fact that as the silt would be deposited in the Reservoir the use of clear water for irrigation would not maintain a soil-fertility as had the previous silty water. This may recall a principle that has been stated; that is, that the silts carried by streams may be soil-builders but are not important in maintaining fertility. One thing which this type of silt-laden water is highly valuable for is the modification that can be produced by its use on extremely sandy land which can by a controlled use of the water in the irrigation of crops on the land result in altering its characteristics to form a rather satisfactory soil-condition.

In closing it may be recalled that attention has been directed to the fact that any system of control which would appreciably decrease erosion would also to some extent at least decrease the runoff from the drainage-area. While there are good grounds for such a statement and it undoubtedly is quite correct, it may be stated that in the case of Elephant Butte Reservoir a rather small percentage of the total runoff of the Rio Grande Drainage-Area above the Reservoir carries in or is responsible for a very large percentage if not practically all of the silt entering the Reservoir. The reason for this is that practically all of the silt comes from the tributaries of the River entering from the broken, generally barren, central part of New Mexico, the runoff from which is confined to summer floods of short duration and, while they often reach maximum flood-peaks, they do not usually last long enough to produce a considerable volume of water. The comparatively silt-free spring floods produced by melting snow in the mountains of northern New Mexico and southern Colorado are normally relied upon for the replenishment of the irrigation supply- and storage-increments.

The situation as it pertains to Elephant Butte Reservoir may then be summed up as follows: Any silt-retention works or soil-erosion control-system which could be instituted on the Rio Grande watershed in the central part of New Mexico would be a great asset to the Rio Grande Irrigation-Project. Since the water-supply coming from that area is not usually of any great consequence and since it does produce practically all of the silt, the consequent extension of the useful life of the Reservoir would undoubtedly be more valuable to the Project than the relatively small amount of water which may be lost to the Project thereby.

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DYNAMIC ACTION OF RAINS IN RELATION TO EROSION IN THE HUMID REGION

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Although accelerated runoff of rain-water and consequent speeded-up erosion resulting from man's removal of the natural cover of vegetation and disruption of the normal porosity of the soil with plows and domestic animals alter the ground-surface more than any other physical agency, save perhaps the light of the sun, the fundamental processes involved with these artificially-induced changes of natural soil-conditions have not been recognized or studied in any systematic manner until within the past fifteen years. More than all other physical agencies with which man has any causative association, accelerated erosion is responsible for soil-impoverishment and eventual soil-destruction. Fully 75 per cent of the crop-producing and grazing areas of the United States is sloping enough to set in motion, moderately or violently, these wasteful processes of accelerated soil-removal and excessive runoff. That 35 million acres of formerly cultivated land have been essentially ruined by erosion and that an additional area of about 125 million acres, still largely in cultivation, have lost all or most of the topsoil, with another 100 million acres of crop-land heading in this direction, should be sufficient evidence that the problem is one of profound economic importance. Especially must this be considered true since the wastage is now proceeding faster than ever, owing to the fact that considerable time was required to strip off the more absorptive surface-layer from millions of acres, and to the further fact that the subsoil is generally more erosive than the soil. The cost runs into hundreds of millions of dollars annually, in the way of direct depreciation and essential destruction of fields and pastures, the silting of reservoirs, stream-channels and ditches, damage to highway and railway fills and embankments, choking of culverts, covering of valuable valley-lands with relatively unproductive erosional debris, and pollution of former clear-water streams with excessive loads of silt and clay washed out of the hills.

This paper, however, is not so much concerned with the economic significance of accelerated soil-washing as with those processes of erosion that pertinently relate to rates of rainfall-absorption, runoff, and soil-removal, and with some of the more important of the numerous variables involved.

Multiplicity of variables

It would be difficult to conceive a physical agency involving more modifying factors than the process of land-erosion. Not only are the interdependent processes of absorption, runoff, and erosion profoundly affected by slope, climate, soil, and cover of vegetation and vegetative litter, but by the condition of the surface-soil resulting from various methods of utilization, and, subsequently, by the condition and character of the different sub-layers successively exposed by planation. These and numerous other factors, separately and interdependently, introduce into the dynamics of this three-phased process an almost inconceivable number of highly pertinent variables.

Soil-type alone introduces an almost endless variety of conditions that appreciably and even profoundly affect rates of absorption and, therefore, of runoff and soil-denudation. The texture of the surface-material, its inherent structure and consistency, markedly affect rates of absorption, as do also the same characteristics expressed in the widely divergent sub-layers through the soil-profile down to and including the horizon of parent material. Obviously, rain-water passes down into and through coarse sand at a much more rapid rate than through dense clay. Again, the capacities of sand or of sandy loam, fine sandy loam, silt-loam, and other pervious materials for absorbing rainfall vary markedly with varying depth to sub-layers of relatively impervious material, as plastic clay and hardpan. When it is considered that there are several thousand distinct soil-types in the United States, and that these occupy a great variety of slopes, subjected to a multiplicity of uses and intensities of rainfall, we begin to develop some conception of the great range of pertinent variants, such as can not be ignored either in research or in the development of practical methods for controlling erosion. After considering the long list of these more evident factors, it must be rather appalling to the specialist interested in working out control-measures that he must deal with still other categories of variables, the physical behaviors of which are not so obvious. I think it is safe to assert that we do not know any too much about the mechanical relation of gravitational creep, solifluction, sliding, or of soil-fragmentation, granulation, and dispersion to processes and rates of runoff and erosion. Very few really understand the causative processes involved with the formation of V-shaped gullies, as distinguished from U-shaped gullies or gullies that cut faster laterally than longitudinally. Differential erosion on exposed sections of soil-profiles characterized by markedly different horizons is a thing that lies rather completely outside the knowledge of most specialists. Very little is known about the dynamics of rill-washing. And then, the baffling contrasts revealed in measurements of runoff and erosion from the same soil, occupying the same degree of slope and subjected to the same cultural treatments, should be enough to convince any one that the mechanics of loading and unloading on the part of thin and thick sheets of water flowing across slopes of different lengths is little understood.

It must indeed be somewhat confusing when specialists who have devoted years of study to the problem of erosion admit that we still stand only at the threshold of knowledge relating to the subject, but such is the situation, nevertheless. The investigations thus far carried out have led us at least far enough to recognize that we are faced by a variety of erosional behaviors that we do not at all understand.

What I have said may seem to carry a tone of discouragement and hopelessness. This is not meant at all; Briefly, soil-erosion presents a new and very large field for research and for practical work. The field has been neglected; we have not studied the problem enough to have solved all of the fundamentals. We have, however, acquired enough information at the various erosion experiment-stations and through erosion-surveys and soil-surveys to know that we have made a real beginning with soil-erosion investigations.

Runoff and erosion from different soils undergoing various cultural treatments

[The measurements referred to here and in the subsequent pages were carried out under the experimental erosion-program of the Bureau of Chemistry and Soils, United States Department of Agriculture, except those at Spur, Texas, and at Columbia, Missouri, which were under the direction of the respective state experiment-stations. The program in the Bureau of Chemistry and Soils was planned and developed by the writer. The results obtained at Bethany, Missouri, were carried out under the immediate supervision of R. E. Uhland; those at Clarinda, Iowa, under G. W. Musgrave; those at Statesville, North Carolina, under J. M. Snyder; those at Temple, Texas, under H. V. Geib; those at Tyler, Texas, under B. H. Hendrickson; those at Guthrie, Oklahoma, under S. W. Phillips and H. G. Lewis; those at Spur, Texas, under R. E. Dickson; those at Columbia, Missouri, under F. M. Miller, H. H. Krusekopf, and F. L. Duley; those at Hays, Kansas, under R. H. Davis and O. E. Hays; and those at La Crosse, Wisconsin, under R. H. Davis.]

Let us turn to some of the facts that are gradually coming to light. Beginning with measurements made at the Bethany, Missouri, erosion-station on one of the most extensive soils in the rolling sections of the corn-belt, the Shelby silt-loam and its very close relative, Shelby loam, derived from the glacial till of northern Missouri, southern Iowa, northeastern Kansas, and southeastern Nebraska, we find that from about the average regional slope (eight per cent) the annual soil-loss from a representative cross-section of a strip 73 feet wide has amounted to approximately 60 tons an acre, along with a loss of 27 per cent of the total precipitation, where corn is grown continuously. As against this, the loss from exactly the same kind of soil, having the same declivity and receiving the same rainfall, the corresponding losses from areas devoted to thick-growing crops have been very much less. Under alfalfa there has been a loss of only 0.2 ton of soil per acre annually, along with a runoff of only a little over three per cent of the precipitation, and under timothy only 0.3 ton of soil and about eight per cent of the precipitation have been lost. In other words, alfalfa has been about three hundred times and grass about two hundred times more effective than corn in the matter of holding soil. The respective efficiencies of the two crops in relation to rainfall-retention, as compared with corn, have been approximately nine and three times as great. For the same period, the same type of land kept bare of all vegetation has lost an average of 112 tons of soil per acre per annum, or more than five hundred times as much as from fields devoted to alfalfa. Strange to say, however, the water-loss from this bare fallow was somewhat less than that from the corn-area where less than half as much soil has been stripped off. From fields under a four-year rotation of corn, wheat, and clover, the loss of soil has proceeded at the rate of about ten tons an acre annually, while the water-loss has been at the rate of 11 per cent of the precipitation, showing that a good crop-rotation is a very effective method for minimizing erosion.

These results represent averages of the three-year period from 1931 to 1933, inclusive, during which time the mean annual precipitation has been 33 1/2 inches. Over this period 208 rains have fallen, 70 of which (or 33 per cent) caused runoff. Of the 42 1/2 inches of rainfall in 1931, 31 rains caused runoff from corn-ground, these totaling 29.7 inches. Although only 16 of the 62 rains that fell in 1932 produced runoff, 19 of the 62 amounted to more than one inch each. Many light summer showers were completely dissipated by almost immediate evaporation from the heated soil. Under certain conditions some of the heavier rains, even where falling at a fairly intense rate, have been completely absorbed, while under other conditions lighter rains of about equal intensity have produced runoff.

In 1931, 30 per cent of all the rain that fell on the continuous corn-plot (Plot 2) at the Bethany Station was lost as runoff. That year 39 rains, totaling 12.8 inches, or 30 per cent of the total precipitation, produced no runoff from this plot. More than half of this 30-per cent fraction of the rainfall fell in the form of light showers that immediately evaporated. Thus, the immediate loss of rainfall for this period amounted to something over 45 per cent of the total precipitation. Since part of the remainder was lost as percolation and part as evaporation other than transpiration, the corn-crop had for its use probably considerably less than half of the rainfall--perhaps something under 40 per cent.

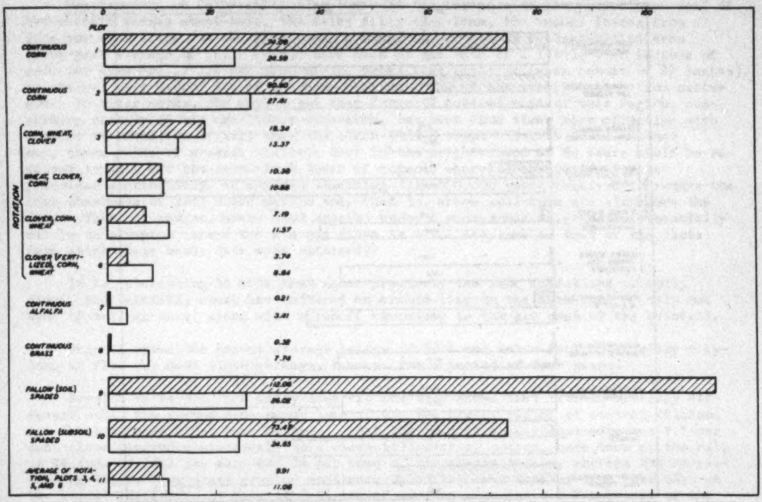
In contrast, only two per cent of the rainfall of 1931 was lost from the alfalfa field (Plot 7). Thus, this densely growing crop had for its use, on the same slope and soil, and with the same rainfall, possibly in the neighborhood of 68 per cent of the total precipitation. Accordingly, quantitative references to effective precipitation must be specific if they are to have any significance.

These results, as already noted, are based on a three-year period. This, of course, is not long enough for the establishment of absolutely accurate averages. Nevertheless, the results probably are nearly enough accurate to be highly significant. It might be mentioned in this connection that the soil-depth of the Shelby silt-loam on eight per cent slopes, in the locality where these data were obtained, is approximately seven inches, and that the rate of soil-stripping under continuous corn-production, as revealed in these measurements, would require, theoretically, about twenty years to remove the surface-layer down to a distinctly different sub-layer, having a different rate of erosion. Actually, a somewhat longer period would be required for the removal of this much soil, because some of the subsurface material would be brought up and mixed with the topsoil by plowing.

That a three-year period of measurements is inadequate for final conclusions with respect to rates of erosion and runoff is indicated by the soil- and water-losses from a single intensive rain of 3.7 inches that fell on these plots on April 3, 1934 (3.03 inches of which fell at an average rate of 2.36 inches an hour). From continuous corn the loss of soil as the result of this one rain was nearly as great as the entire loss caused by all of the 76 rains that fell on this same plot in 1933, that is, 46 tons as against 56 tons. From this exceptional rain 69 per cent of the water was immediately lost as runoff, whereas only 27 per cent of the total rainfall of 1933 was lost from the same corn-plot.

Graphs 1, 2, and 3 show the details of soil- and water-losses from Shelby silt-loam occupying eight per cent slopes at Bethany, Missouri, as annual averages for a three-year period, for a one-year period, and for a single exceptionally heavy downpour. Graph 4 shows the corresponding losses from a 3.68-per cent slope of Shelby loam at Columbia, Missouri, as annual averages for a 14-year period.

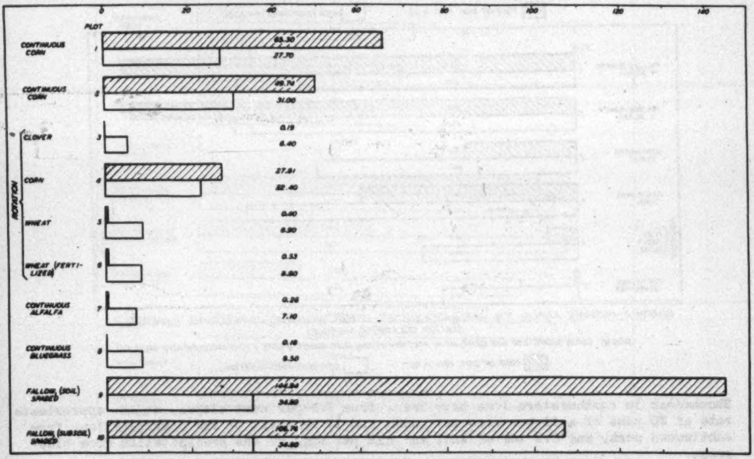
Loss from Marshall silt-loam--From another variety of silt-loam, the extensive Marshall silt-loam of the Missouri Valley loessial area, the losses measured over a period of 1 1/2 years at the erosion experiment-station between Clarinda and



GRAPH 1—AVERAGE ANNUAL SOIL AND WATER LOSSES, 1931-33 INCLUSIVE, EROSION EXPERIMENT STATION, BETHANY, MISSOURI

SHELBY SILT-LOAM, SLOPE 8 PER CENT; MEAN PRECIPITATION, 33.54 INCHES (PLOT 1=6 X 145.7 FT.; PLOTS 2 TO 10 INCLUSIVE=6 X 72.85 FT.)

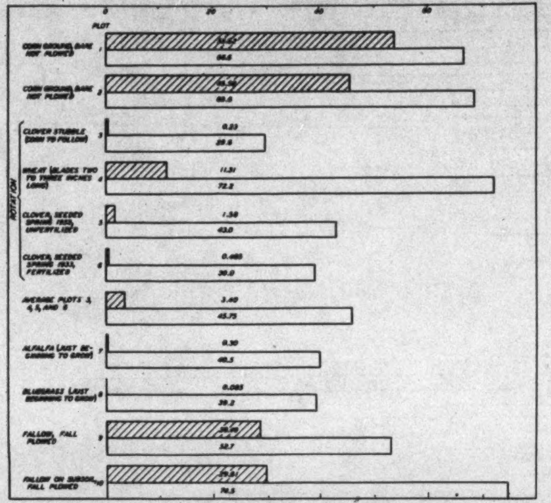
▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION



GRAPH 2—SOIL AND WATER LOSSES, 1933, EROSION EXPERIMENT STATION, BETHANY, MISSOURI

SHELBY SILT-LOAM, SLOPE 8 PER CENT; PRECIPITATION, 31.06 INCHES (PLOT 1=6 X 145.7 FT., PLOTS 2 TO 10 INCLUSIVE=6 X 72.85 FT.)

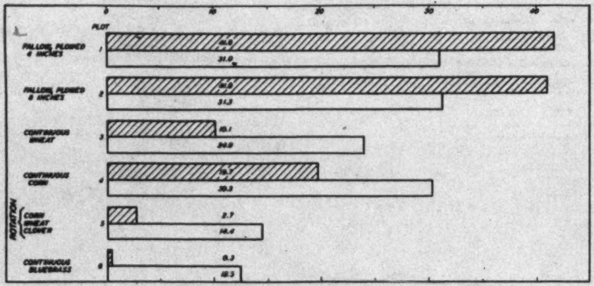
▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION



GRAPH 3—RESULT OF ONE RAIN OF 3.71 INCHES, APRIL 3, 1934, EROSION EXPERIMENT STATION, BETHANY, MISSOURI

SHELBY SILT-LOAM, SLOPE 8 PER CENT; 3.30 INCHES FELL AT RATE OF 2.36 INCHES PER HOUR (PLOT 1=6 X 145.7 FT, PLOTS 2 TO 10 INCLUSIVE=6 X 72.85 FT.)

▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION



GRAPH 4—AVERAGE ANNUAL SOIL AND WATER LOSSES, 1918-31 INCLUSIVE, AGRICULTURAL EXPERIMENT STATION, COLUMBIA, MISSOURI

SHELBY LOAM, SLOPE 3.68 PER CENT; MEAN PRECIPITATION, 40.37 INCHES (PLOTS 1 TO 6 INCLUSIVE=6 X 90.75 FT.)

▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION

Shenandoah in southwestern Iowa have been, from 9.6-per cent slopes, at the approximate rate of 30 tons of soil per acre per annum and 12 per cent of the precipitation, from continuous corn, and 0.9 ton of soil and six per cent of the precipitation from bluegrass.

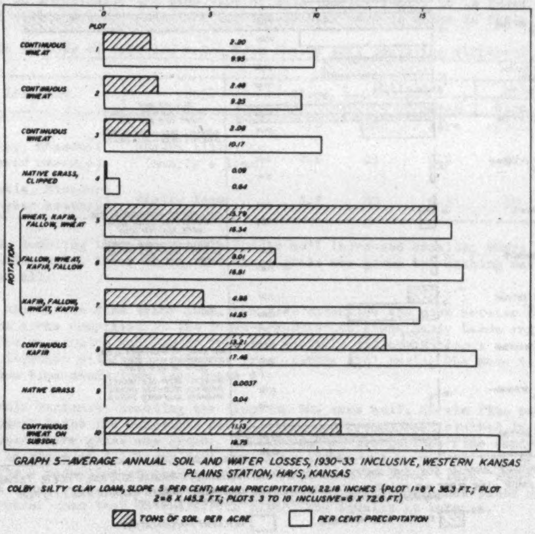
The variety of silt-loam on which these measurements were made differs from the Shelby silt-loam in having a higher content of silt and lower content of sand and fine gravel.

Measurements on Colby silty clay-loam--In the instance of the predominant soil of the western Kansas wheat-belt, the Colby silty clay-loam, the annual losses from a five per cent slope (at the Hays erosion-station) devoted to a clean-tilled crop (four-year average of Kafir corn), have been at the rate of a little over 13 tons of soil per acre and 17 1/2 per cent of the total precipitation (mean annual of 22 inches), as against only 0.0037 ton of soil and 0.04 per cent of the precipitation from native sod. In other words, the native sod that formerly covered most of this region, consisting chiefly of big and little blue-stem, has been 3500 times more effective with respect to retention of soil than the clean-tilled crop. Expressed in another way, these rates of erosion indicate that in the neighborhood of 90 years would be required to wash off the seven-inch layer of topsoil where clean-cultivation is practiced continuously, as against something like 300,000 years required to remove the same thickness of soil under native sod, that is, where soil-type and slope are the same. This, of course, means that erosion under a good cover of grass is essentially nil in this region (where the average slope is about the same as that of the plots from which these basic data were obtained).

It is interesting to note that under precisely the same conditions of soil, slope, and rainfall, wheat has suffered an annual loss on the same farm of only two tons of soil an acre, along with a runoff amounting to ten per cent of the rainfall.

Graph 5 shows the annual average losses of soil and water from Colby silty clay-loam of five per cent slope at Hays, Kansas, for a period of four years.

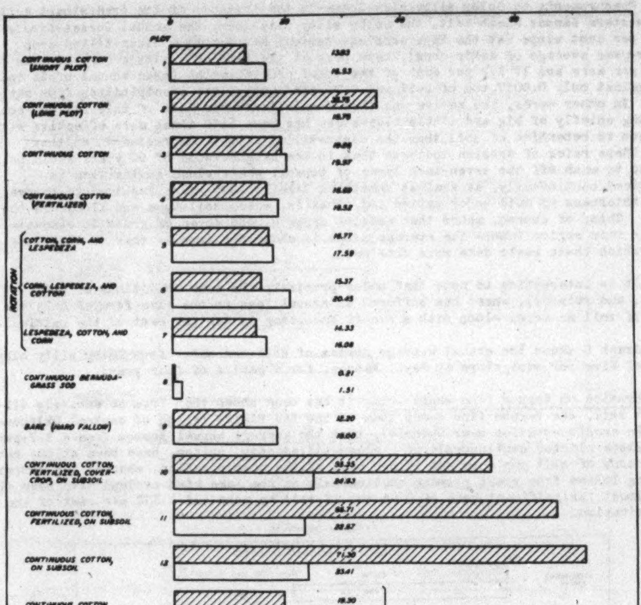
Erosion on Vernon fine sandy loam--It has been shown that from an entirely different soil, the Vernon fine sandy loam of the Red Plains region of central Oklahoma (at the erosion-station near Guthrie), that the average annual losses from a 7.7-per cent slope planted continuously to a clean-tilled crop, cotton, have been at the rate of 28 tons of soil per acre and 14 per cent of the precipitation, whereas the corresponding losses from grass growing continuously on the same kind of land have been at the almost insignificant rate of 0.04 ton of soil an acre and 1 1/2 per cent of the precipitation.



GRAPH 5—AVERAGE ANNUAL SOIL AND WATER LOSSES, 1930-33 INCLUSIVE, WESTERN KANSAS PLAINS STATION, HAYS, KANSAS

COLBY SILTY CLAY LOAM, SLOPE 5 PER CENT; MEAN PRECIPITATION, 22.18 INCHES (PLOT 1=6 X 36.3 FT.; PLOT 2=6 X 145.2 FT.; PLOTS 3 TO 10 INCLUSIVE=6 X 72.6 FT.)

▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION



GRAPH 6—AVERAGE ANNUAL SOIL AND WATER LOSSES, 1931-33 INCLUSIVE, EROSION STATION, TYLER, TEXAS
KIRVIN FINE SANDY LOAM, SLOPE 8.75 PER CENT; MEAN PRECIPITATION, 42.31 INCHES (PLOTS 1, 13, 18 = 6 X 36.5 FT.; PLOT 2 = 6 X 145.8 FT.; PLOTS 3-12, 14-17, 19-21 INCLUSIVE = 6 X 72.9 FT.)

▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION

Losses from Kirvin fine sandy loam--From still another fine sandy loam, the Kirvin fine sandy loam of east Texas (at the Tyler, Texas, erosion-station), the average annual losses from continuous cotton have been at the rate of 19 tons of soil an acre and approximately 20 per cent of the rainfall, as against losses of only one-fifth of a ton of soil an acre and 1 1/2 per cent of the precipitation where a good sod is maintained. In fields of greater width the measured soil-loss has been at a much higher rate (see plot 2, Graph 6). Graph 6 shows the comparative soil- and water-losses from various slopes on Kirvin fine sandy loam and also on Nacogdoches fine sandy loam, where the land was subjected to a variety of treatments.

Losses from Clinton silt-loam--From Clinton silt-loam occupying a 16-per cent slope, near La Crosse, Wisconsin, the losses in 1933, with a rainfall of approximately 29 inches, amounted to 60 tons of soil an acre and 19 per cent of the rainfall, where corn was grown, and 0.003 ton of soil and three per cent of the rainfall from the same kind of land under a cover of blue-grass.

Losses from Cecil sandy clay-loam--From Cecil sandy clay-loam, the most extensive agricultural soil of the North Carolina Piedmont region, the average annual losses from 10-per cent slopes have been at the rate of 14 tons of soil per acre and nine per cent of the total precipitation from cotton fields, as against 0.7 ton of soil and five per cent of the precipitation where grass was grown.

Effect of slope on erosion and runoff

It has been assumed generally that slope is the most powerful factor affecting erosion and runoff. The available data do not bear out this point of view. They indicate instead that the character of the vegetative cover is the most pertinent factor in this connection, and after that the character of the soil appears to have the most potent influence.

Taking up again the results of measurements made at Bethany, Missouri, and comparing these with the results obtained at the state experiment-station at Columbia, Missouri, on practically the same type of soil (Shelby loam), it is found that the losses of soil and water under the two declivities were as shown in Table 1.

Table 1--*Loss of soil and water from Shelby soil occupying different slopes*

Location	Soil	Slope	Soil-loss		Water-loss	
			Corn	Grass	Corn	Grass
		o/o	tons per acre		o/o of precip.	
Bethany, Missouri (4-year average)	Shelby silt-loam (nearly a loam)	8.0	61	0.3	27	8
Columbia, Missouri (14-year average)	Shelby loam	3.7	20	0.3	30	13

Thus, doubling the slope on the Shelby soil increased erosion, where corn was grown continuously, three times, but where grass was grown the washing was not increased at all.

For the Kirvin fine sandy loam, the most extensive and most erosive soil of the 33 million acres comprised in the Texas-Arkansas-Louisiana Sandy Lands region, data of comparative erosion and runoff from two markedly different slopes are shown in Table 2, together with similar losses from another soil having the same texture--the Nacogdoches fine sandy loam (see Graph 6).

In this instance, doubling the slope on the same soil, Kirvin fine sandy loam, caused almost twice the soil-loss where cotton was grown, but resulted in no increased loss where grass was grown. In the case of Nacogdoches fine sandy loam, an increase in slope of 1 1/4 per cent over that of the nearby Kirvin fine sandy loam was followed by a reduction of the erosion to the extent of three times, under cotton, and ten times under grass, even though the rainfall on the Nacogdoches plots was 2 1/3 inches greater than that on the Kirvin plots, and equally as intense.

Table 2--Loss of soil and water from Kirvin and Nacogdoches soils, east Texas

Location	Soil	Slope	Soil-loss		Water-loss	
			Cotton	Grass	Cotton	Grass
	fine sandy loam	o/o	tons per acre		o/o of precip.	
Erosion-station, near Tyler, Texas	Kirvin	8.75	19	0.2	20	1.5
Erosion-station, near Tyler, Texas	Kirvin	16.50	35	0.0	13	0.7
Erosion-station, near Tyler, Texas	Nacogdoches	10.00	6	0.02	15	1.4

A very interesting relationship of slope to erosion is afforded by the measurements made on the Abiline clay-loam at Spur, Texas. Here the average soil-loss from level land over a period of eight years has been at the rate of three tons per acre annually under continuous cotton. The corresponding losses on slopes of one and two per cent have been at the rates of six tons and eight tons per acre.

Considering slope, the losses of both soil and water from the extensive Cecil sandy clay-loam of the North Carolina Piedmont have been remarkably low, namely, only 14 tons of soil lost per acre under cotton grown on 10-per cent slopes, along with only nine per cent of the rainfall lost as runoff. Comparing these results with those obtained on a 2-per cent slope of Abiline clay loam at Spur, Texas, it is seen that, although the slope of the North Carolina clay-loam was five times as steep and the rainfall more than twice as heavy (43 inches, against 21 inches) and more torrential, the erosion from cotton grown on this Piedmont land was only a few tons greater (14 against eight tons), while the runoff was actually less (nine per cent against 14 per cent).

This was due to the fact that the North Carolina clay-loam is very different physically from the west Texas clay-loam. It is of lateritic character. The material of lateritic soils, that is, highly-weathered soils, does not go into suspension in water as rapidly as the material of less-oxidized and less-leached soils of the same texture, such as the Abiline clay-loam. This property alone gives considerable resistance against erosion. It may be of interest to add here that some of the clay-laterites of the tropics are almost proof against erosion [see H. H. Bennett, Some comparisons of the properties of humid-tropical and humid-temperate American soils, Soil Sci., v. 21, No. 5, May 1926, pp. 349-374, and H. H. Bennett and R. V. Allison, The soils of Cuba, Tropical Plant Research Foundation (Boyce-Thompson Institute, Yonkers, New York), 1928]. The red-basalt soils of western Oregon are also somewhat of this nature, suffering but slightly from washing on very steep cultivated slopes.

Comparison of protective efficiency of grass and forest

Table 3 shows the effects of forest-cover and grass on erosion and runoff, as measured on the Kirvin fine sandy loam in east Texas (see Graph 1) and on Vernon fine sandy loam in central Oklahoma. In both instances the ground-cover of litter was decidedly light as compared with the average forest-floor litter of the country.

Table 3--Effect of forest on erosion and runoff, as compared with grass, Tyler, Texas, and Guthrie, Oklahoma

Soil	Mean precip.	Slope	Cover	Soil-loss	Water-loss
fine sandy loam	inches	o/o		tons per acre	o/o of precip.
Kirvin	44.4	12 1/2	Forest	0.01	0.8
Kirvin	44.4	12 1/2	Forest, litter burned	0.19	2.6
Kirvin	42.3	8 3/4	Bermuda grass	0.21	1.5
Kirvin	48.8	16 1/2	Bermuda grass	0.00	0.7
Vernon	33.5	5 1/5	Forest	0.017	0.13
Vernon	33.5	5 1/5	Forest, litter burned	0.22	5.06
Vernon	32.9	7 7/10	Bermuda grass	0.04	1.5

These results show that forest, as well as good stands of grass, give practically complete protection from erosion on these very extensive and important soil-types. The water-losses also have been exceedingly small, especially where the ground-cover of forest-litter has not been burned. The difference between the effectiveness of grass and forest is seen to be very slight.

For four years the average runoff from the burned forest-area in Oklahoma has exceeded by three times the loss from precisely the same area having the same forest-cover, soil, and slope, and receiving the same rainfall, where the organic ground-cover remained intact, while the corresponding soil-loss has been 19 times as great. Measurements of runoff from these plots made during a very wet period in May 1930, showed that the unburned area lost rainfall at the rate of 250 gallons per acre, while the burned plot lost 27,600 gallons per acre. The excess of runoff from the burned area over that from the unburned area, plus the water-holding capacity of the leaf-litter covering the latter site, was approximately 90 tons an acre. Thus, the protective effect of a thin cover of leaves is seen to be greater than the capacity of such ground-cover to absorb soil--about 5 1/2 times as great in this instance (see H. H. Bennett, Relation of erosion to vegetative changes, Sci. Mon., v. 25, November 1932, pp. 385-415, and W. C. Lowdermilk, Influence of forest-litter on runoff, percolation, and erosion, J. Forestry, v. 28, No. 4, 1930).

Effect of removal of surface-soil on erosion and runoff

Generally erosion increases following removal of the surface-soil by sheet-washing, and it is at this stage of progressive erosion that gullying, the beginning of the final stage of land-destruction, usually sets in. Table 4 shows comparative rates of erosion and runoff from surface-soil and subsoil of a number of extensive soil-types. In the instances of each of these important types, representing collectively many millions of acres of farm-land, the losses of both soil and water have been greater where the subsoil was exposed to the rains under precisely the same conditions of slope, treatment, and rainfall. In one instance the loss of material from subsoil exceeded that from the corresponding surface-soil (both areas having been originally the same) by six times. The average loss of soil-material and of water from subsoil exceeded the corresponding losses from surface-soil by 98 and 44 per cent, respectively.

Table 4--Soil- and water-losses from soil and subsoil of important types originally the same

Location	Soil	Slope	Cover	Mean precip.	Soil-loss		Water-loss	
					Surface-soil	Sub-soil	Surface-soil	Sub-soil
		o/o		inches	tons per acre		o/o of precip.	
Tyler, Texas	Kirvin fine sandy loam	8.75	Cotton	42	19	71	20	23
Tyler, Texas	Nacogdoches fine sandy loam	10.0	Cotton	44	6	36	15	19
Guthrie, Oklahoma	Vernon fine sandy loam	7.7	Cotton	33	28	32	14	28
Clarinda, Iowa	Marshall silt-loam	9.6	Corn	48	45	81	13	15
Hays, Kansas	Colby silty clay-loam	5.0	Wheat	22	2	11	10	19
La Crosse, Wisconsin	Clinton silt-loam	16.0	Corn	29	60	89	19	30
Statesville, N.Carolina	Cecil sandy clay-loam	10.0	Cotton	43	14	17	9	8
Temple, Texas	Houston black clay	4.0	Corn, oats, cotton	27	2	11	4	8

Effect of crop-rotations on soil- and water-conservation

Table 5 shows the effect of crop-rotations on erosion and runoff for a number of important soil-types. In every case crop-rotations materially reduced the losses of soil, as compared with the losses from the same kind of land, occupying the same declivity and receiving the same rainfall, where a clean-tilled crop was grown, and in all but one instance the runoff from areas under continuous clean-tillage was greater. The saving of soil ranged up to six times as much as where a one-crop system of clean culture was practiced, with a corresponding conservation of rainfall amounting to nearly three times as much, as was conserved under clean tillage. The average saving over single-crop culture for the eight types amounted to 164 per cent of soil and 37 per cent of water.

Table 5--Comparison of soil- and water-losses under crop rotations on eight important soils

Location	Soil	Slope	Rotation	Mean precip.	Soil-loss	Water-loss
		o/o		inches	tons per acre	o/o of precip.
Bethany, Missouri	Shelby silt-loam	8	Corn, wheat, clover	34	10	11
Columbia, Missouri	Shelby loam	3.7	Corn, wheat, clover	40	10	24
Hays, Kansas	Colby silt clay-loam	5	Wheat, kafir, fallow	22	10	16
Guthrie, Oklahoma	Vernon fine sandy loam	7.7	Wheat, sweet-clover, cotton	33	6	12
Temple, Texas	Houston black clay	4	Cotton, corn, oats	27	6	5
Tyler, Texas	Kirvin fine sandy loam	8.75	Cotton, corn, lespedeza	42	16	18
La Cross, Wisconsin	Clinton silt clay-loam	16	Barley, corn, clover	29	21	13
Statesville, North Carolina	Cecil sandy clay-loam		Corn, wheat, lespedeza, cotton	43	7	10

Effect of tillage methods on soil- and water-conservation

Table 6 shows the effect of various soil-modifications on soil- and water-losses from four extensive soil-types. It will be observed that these effects were very marked in some instances, especially the saving of soil and water by contouring versus cultivation down-hill, and with closed-end level terraces and scarification of the surface with a hole-digging machine.

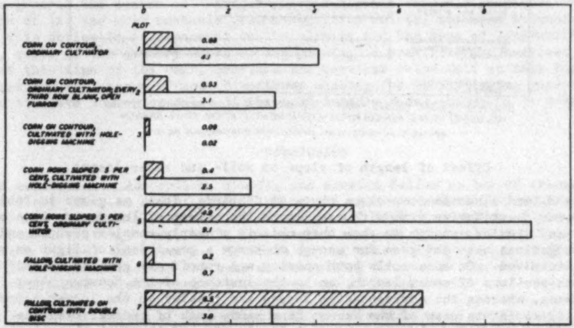
Graphs 7 and 8 show the details of losses occurring from differently-treated areas at La Cross, Wisconsin, and at Spur, Texas.

Effect of incorporating organic matter on soil- and water-losses

Table 7 shows the beneficial effect of organic matter plowed into the soil in minimizing soil- and water-losses. These preliminary data indicate that within certain limitations addition of organic matter appreciably reduces both erosion and runoff. Quantitative information on this subject, however, is entirely inadequate for reaching any very definite conclusions as to what kind and how much organic matter should be used.

Table 6--Soil- and water-losses from four important soils undergoing different mechanical treatments

Treatment	Slope	Precip.	Soil-loss	Water-loss
	o/o	inches	tons per acre	o/o of precip.
		Spur, Texas--Abiline clay-loam		
Cotton, level terraces closed at ends	0.5	18.5	0.0	0.0
Cotton, contoured rows	0.5	18.5	...	6.8
Cotton, rows down slope	0.5	18.5	...	8.8
		La Crosse, Wisconsin--Clinton silt-loam		
Corn, ordinary cultivator on contour	16	14	0.7	4.1
Corn, cultivated on contour with hole-digger	16	14	0.09	0.02
Corn, rows sloped 5%, ordinary cultivator	16	14	4.9	9.1
Corn, rows sloped 5%, cultivated with hole-digger	16	14	0.4	2.5
		Guthrie, Oklahoma--Vernon fine sandy loam		
Cotton, rows down slope	6.8	35	59.	13.7
Cotton, rows contoured	6.9	35	21.	11.3
		Hays, Kansas--Colby silty clay-loam		
Fallow, double-disc	4.	14	2.8	10.8
Fallow, hole-digger	4.	14	0.6	3.9
Fallow, duckfoot down slope	4.	14	3.4	13.9
		Clarinda, Iowa--Marshall silt-loam		
Corn, rows down slope (plot 42' x 630')	8.4	26	34.5	9.4
Corn, rows down slope (plot 42' x 315')	8.4	26	20	9.5
Corn, rows down slope (plot 42' x 157!.5)	8.4	26	11.	11.5
Corn, rows on contour (plot 42' x 157!.5)	8.4	26	0.0	0.0



GRAPH 7--SOIL AND WATER LOSSES FROM DIFFERENT TILLAGE TREATMENTS, JULY 1 TO DECEMBER 31, 1933, EROSION EXPERIMENT STATION, LA CROSSE, WISCONSIN

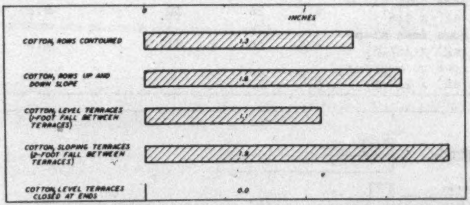
SLOPE 16 PER CENT; RAINFALL, 13.9 INCHES (PLOTS 1 TO 7 INCLUSIVE=1/30 OF AN ACRE)

▨ TONS OF SOIL PER ACRE ☐ PER CENT PRECIPITATION

Table 7--Soil- and water-losses from two important soils with incorporated vegetable matter

Treatment	Slope	Precip.	Soil-loss	Water-loss	Yield per acre
	o/o	inches	tons per acre	o/o of precip.	
			Tyler, Texas--Kirvin fine sandy loam		
Cotton, no treatment[a)]	6.5	24	9.5	0.7	1120 lbs
Cotton, 15 tons oak leaves per acre	6.5	24	2.4	0.2	1410 lbs
Cotton, 10 tons compost per acre[a)]	6.5	24	8.6	0.5	1295 lbs
Cotton, 10 tons manure per acre[a)]	6.5	24	8.6	0.6	1385 lbs
			Clarinda, Iowa--Marshall silt-loam		
Corn, no treatment[b)]	8.8	40	50.	15.	40 bu
Corn, 8 tons manure per acre[b)]	8.8	40	18.	9.	64 bu
Corn, 16 tons manure per acre[b)]	8.8	40	12.	5.	85 bu
Corn, green sweet-clover low rate[b)]	8.8	40	8.	7.	100 bu
Corn, green sweet-clover high rate[b)]	8.8	40	12.	6.	106 bu

[a)] Period July 1, 1932, to December 31, 1933. [b)] Period August 1, 1932, to December 31, 1933.



GRAPH 8--RUNOFF LOSSES FROM FIELD AREAS, 7-YEAR AVERAGE, (1927-33 INCLUSIVE) TEXAS AGRICULTURAL EXPERIMENT STATION, SPUR BRANCH

ABILINE CLAY LOAM, MEAN ANNUAL PRECIPITATION, 18.46 INCHES

Effect of length of slope on soil- and water-losses

Table 8 (and also the down-slope plots at Clarinda, Iowa, as given in Table 6) includes some quantitative data with respect to the effect of length of slope on rates of runoff and erosion, enough to show that this is a deeply complex problem and that our investigations have not gone far enough to throw a great deal of light on the mechanics involved. On some soils both erosion and runoff are greater on uniform slope cross-sections of short length, as in the instance of the Houston black clay of central Texas, whereas the corresponding losses are greater on the longer slopes of other soils, as in the case of the Vernon fine sandy loam of central Oklahoma. This is a matter not easy of explanation, especially in view of the fact that similar results have been obtained year after year.

Table 8--Effect of length of slope on erosion and runoff

Location	Soil	Slope	Precip.	Treatment	Slope-length	Soil-loss	Water-loss
		o/o	inches		feet	tons per acre	o/o of precip.
Guthrie, Oklahoma	Vernon, fine sandy loam	7.7	3.3	Cotton	36.3	23	15
		7.7	3.3		72.6	28	14
		7.7	3.3		145.2	40	14
Temple, Texas	Houston, black clay	4.	27.	Corn	36.3	15	13
		4.	27.		72.6	12	12
		4.	27.		145.2	11	10
Tyler, Texas	Kirvin, fine sandy loam	8.75	42.	Cotton	36.3	13	17
		8.75	42.		72.6	19	20
		8.75	42.		145.2	36	19
La Crosse, Wisconsin	Clinton, silty clay-loam	16.	29.	Corn	36.3	12	19
		16.	29.		72.6	60	19
		16.	29.		145.2	68	15
Bethany, Missouri	Shelby, silt-loam	8.	34.	Corn	72.6	61	27
		8.	34.		145.2	74	25
Clarinda, Iowa	Marshall, silt-loam	9.4	32.	Corn	36.3	47	12
		9.4	32.		72.6	45	13
		9.4	32.		145.2	48	12
Hays, Kansas	Colby, silty clay-loam	5.	22.	Wheat	36.3	2.2	10
		5.	22.		72.6	2.1	10
		5.	22.		145.2	2.5	9

Relation of season to erosion

Generally erosion proceeds at the most rapid rate during spring and summer, especially in the humid Eastern States. In the Pacific Northwest, specifically in the Palouse wheat-belt of southeastern Washington and of adjacent Idaho and Oregon, the most violent erosion normally is caused by melting snow from December to March in fields of winter wheat which have been seeded on summer-fallowed ground. August and September generally are the months of most excessive soil-washing in the arid and semi-arid grazing regions of much of the Southwest.

In general the season of heaviest erosion is that season represented by a combination of (a) the most unstable ground-condition and (b) the most intensive rainfall. This obviously is dependent on the climate and the type of land-utilization. In many parts of the country where spring plowing is practiced the heaviest erosion comes at this time of the year, provided the heaviest rains fall at this time. In the same locality the season of most disastrous washing for the following year may be delayed until late summer or fall, if the most intense rains chance to be delayed that long.

Conclusion

In conclusion: Absorption, runoff, and erosion follow no law of averages. The variables are numerous and of potent influence. Safe procedure in planning engineering works and agronomic programs for watershed and field-protection, flood-control, prevention of silting, etc., calls for careful analysis of local conditions of soil, vegetation, slope, and climate. To leave any of these highly pertinent factors out of consideration would be much the same as forgetting to examine the substrata of those places where dams or other heavy structures are to be erected.

A very large amount of investigational work remains to be carried out in the field of this three-phase process. A start has been made, but there is the very acute need that specialists having any interest in the land and the behavior of water flowing across the land should lend continuing support to every worthy effort made in the direction of solving the fundamental principles of the process, as well as working out practical control-measures.

Soil Erosion Service,
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Washington, D. C.

DYNAMICS OF EROSION IN CONTROLLED CHANNELS

C. E. Ramser

Nature controls erosion on land-slopes largely by supplying a vegetative covering that protects the ground surface, retards the runoff and permits a larger part of the runoff-water to be absorbed by the soil. Artificial operations of man such as cultivation and overgrazing with livestock, destroys the balance established by Nature resulting in excessive runoff and serious erosion. Man must continue to cultivate the land and grow both clean cultivated row crops that leave the land-surface without protection against erosion during the greater part of the year, and grain-crops that expose the land-surface to serious erosion during periods of seeding and preparation of the soil-bed.

In order to control erosion on both land-slopes and in runoff-channels it is necessary to prevent the runoff-water from attaining a velocity sufficient to erode the soil over which it travels. The erosive power of a stream of water varies as the square of the velocity. Theoretically, the maximum size of particle (as measured by the diameter) which can be transported by a current, assuming bodies of similar shape and substance, varies as the square of the velocity, and their weights assuming equal volumes, as the sixth power of the velocity. However, it has been found by experiment that the weights that can be transported vary more nearly as the fifth power of the velocity.

Clay-soils are characterized by considerable cohesion among the particles and they present greater resistance to erosion than do sandy or silty soils. Excepting very sandy soils it is generally true that a soil that can be eroded can also be transported by the same current. Although clay-soils are more difficult to erode than sandy soils, yet after being worn off, the clay-particles are more easily transported than the sandy particles. Also a stream, particularly in clay-soils, may have a velocity insufficient to erode the channel but capable of transporting silt delivered to the channel.

Silt is transported by a stream in two ways, namely, (1) in suspension and (2) by rolling along the bottom. The amount, however, transported by rolling along the bottom is generally inappreciable for ordinary velocities as compared with that carried in suspension. The power of a stream to transport silt in suspension is derived from the eddies at the bed. The upward component of these eddies tends to prevent the suspended particles from sinking, and the greater the velocity of flow the greater is this upward component. For instance, the eddies generated on one square foot of the bed of a stream hold the silt in suspension in a vertical column above, extending to the surface of the water. With a given density of silt in the water, the longer this column the greater would be the velocity of the water required to support the silt. Hence, it is seen that a relation may exist between the velocity and the depth such that no silting in the channel takes place and for which, if it be already fully charged with silt, the water will not pick up and carry off more material. This velocity is known as the critical velocity. The relation is expressed by Kennedy in the equation

$$V = CD^m = 0.84D^{0.64}$$

in which V = critical velocity in feet per second, D = depth of water in feet, and C and m are constants depending upon the kind of silt. The values C = 0.84 and m = 0.64 were found to be suitable by Kennedy for fine sand such as found in the beds of rivers in the Punjab (India) shortly after they have left the hills. From the foregoing theory it follows that erosion and silting can be controlled to a certain extent by adopting the proper relation between the velocity and the depth of the proposed channel.

A common mistake in predicting the probability of erosion or silting in a channel is to base the estimate upon the fall of the channel alone. Though it is true that the fall is the positive factor that produces velocity through the action of gravity, yet there are two other factors that exert a decided effect upon the velocity. These are the hydraulic radius of the channel and the resistance to flow caused by the roughness condition of the channel. The hydraulic radius is equal to the cross-sectional area divided by the wetted perimeter of the channel. The roughness condition of a channel is represented by the value of "n" in Kutter's formula; the larger the value of "n", the greater the roughness condition and resulting resistance to flow. The velocity varies with these factors about as given in the formula

$$V = C\sqrt{RS}$$

where V = velocity in feet per second, and C = a constant depending for its value on n, S, and R, and is determined from the following formula

$$C = (1.811/n + 41.66 + 0.00281/S)/ \left[1 + [41.66 + (0.00281/S)]\, n/ \sqrt{R}\right]$$

where R = the hydraulic radius and S = slope of the water-surface.

In order to show that the hydraulic radius has a marked influence upon the velocity in a channel, the results of measurements made on two stream-channels are presented. The channel of Twenty Mile Creek in Mississippi has a fall of 6.1 feet per mile, and the channel of Cypress Creek in Tennessee has a fall of 10.1 feet per mile. Although the fall of the Cypress Creek Channel is nearly twice as large as the channel of Twenty Mile Creek, the velocities in the two channels were 3.69 feet per second and 4.57 feet per second, respectively, the velocity being greater in the channel with the smaller fall. This was due almost entirely to the fact that the hydraulic radius was greater in the channel of Twenty Mile Creek, being 7.2 feet as compared with only 3.4 feet in the Cypress Creek Channel. The values of n in the two channels were about the same, being 0.044 and 0.040, respectively.

That a rough, irregular condition of the interior of a channel has a slowing-up effect on the velocity is seen in the results of experiments conducted on two channels having very nearly the same hydraulic radius and fall. Willow Creek in Iowa and Bogue Hasty in Mississippi had hydraulic radii of 5.35 and 6.1 feet and falls of 0.86 and 0.83 foot per mile, respectively. The velocities, however, were 4.46 and 1.86 feet per second due to the fact that the roughness condition of the channels as represented by the value of n were 0.0128 and 0.0353, respectively. There was practically no vegetation in either channel so that the great difference in the velocities was due practically alone to the difference in the roughness and irregularities in the perimeters of the two channels.

That the condition of a channel as represented by a vegetative growth has a decided effect upon the velocity where the fall and hydraulic radius remain the same is shown by experimental results for Ditch No. 1 of the Little River Drainage-District in Missouri. For a condition of this channel with a thick heavy growth of willows, the value of n was 0.073 and the velocity was 0.73 foot per second. Measurements made for a comparatively clean condition of channel before the vegetative growth appeared in the channel gave a value of n of 0.031 and a velocity of 1.29 feet per second, the velocity being about twice as large as when the willows were in the channel. The hydraulic radius and the fall were practically the same before and after appearance of growth in the channel so that the difference in velocity can be attributed solely to the difference in the value of n.

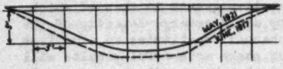

Fig. 1

From the foregoing it is apparent that vegetation in a channel reduces the velocity and thereby erosion. It also protects the channel-surface against the erosive action of the flowing water. Vegetation in the channels of Allen Creek in Iowa promoted silting and prevented erosion. In Figure 1 is shown the reduction in cross-section of chan-

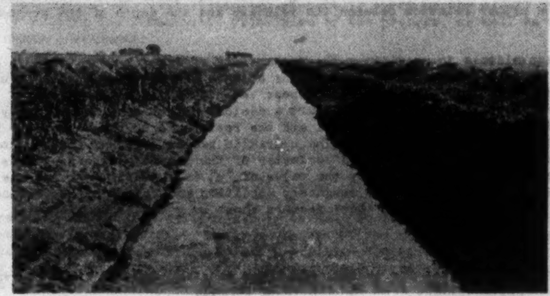

Fig. 2

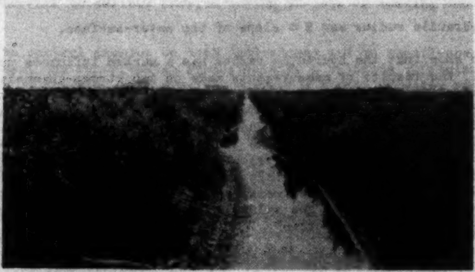

Fig. 3

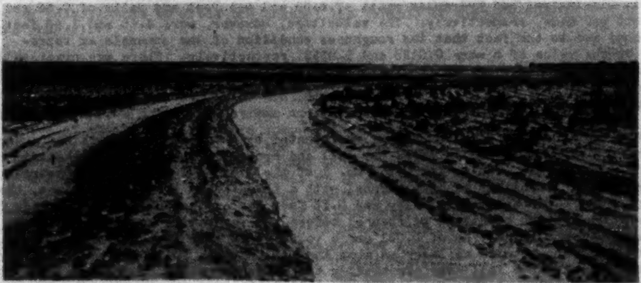

Fig. 5

nel after silting occurred. In Figure 2 is shown clean smooth condition of channel before silting occurred, and in Figure 3 is shown vegetative growth in channel which produced silting and a marked decrease in the velocity and discharge-capacity of the channel. From this it is seen that vegetation in a channel constitutes an excellent method of erosion-control but can only be used as such where no harmful results will follow due to reducing the velocity in the channel and thereby the discharge-capacity.

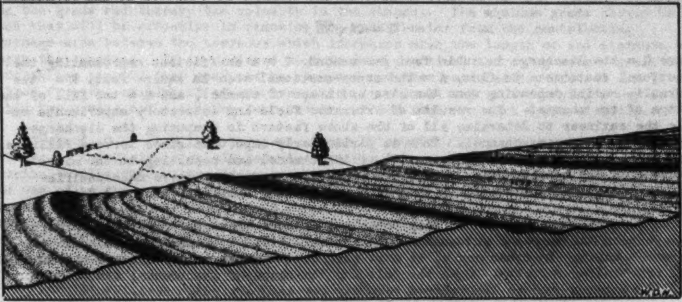

Fig. 4--Ridge-terraces

Since the power of water to cause erosion is dependent upon its velocity and the velocity of the water increases with the slope of the land and the volume of the water (the larger the volume the larger the hydraulic radius for same shaped channel), erosion is more pronounced on steep slopes than on gentle slopes and increases as the volume of runoff-water increases proceeding down a slope. For instance, if the slope is increased four times, the velocity of the water is about doubled and the power of the water to carry away soil is increased about 32 times. Water flowing down a land-slope tends to concentrate in small depressions on the surface forming streams which grow larger in volume approaching the foot of the slope.

In order to prevent the development in the size of such streams of water with their increasing velocities and erosive power, it is necessary to reduce erosion in their channels by vegetation such as permanent sod or to intercept the water at intervals on the land-slope if the land is to be retained in cultivation. Controlling this runoff-water is primarily a problem in hydraulics and its practical application consists of properly planned hillside-drainage, the construction of drainage-channels on hillsides located in such a manner that they will collect the runoff-water and conduct it to a suitable outlet before it attains sufficient velocity to appreciably erode the soil. This method of hillside-drainage is generally known as terracing (see Fig. 4).

The drainage-channels which intercept the runoff-water and prevent its rapid flow down the slope are formed by throwing up broad ridges of soil called terraces. In terracing land the first terrace is constructed near enough to the top of the hillside to collect the runoff-water before it attains sufficient velocity to cause appreciable erosion and the remaining terraces below are spaced at suitable intervals to serve the same purpose. By giving the terrace a fall, the water that collects in the drainage-channel back of the terrace is conducted along the terrace to an outlet ditch usually located along the edge of the field or in a natural watercourse (Fig. 5). The size and fall of this channel must be so chosen that the channel will be able to carry away the runoff-water which is delivered to it from the drainage-area between the terraces without the possibility of the water overtopping the terrace.

From the foregoing it is evident that terraces should be spaced close enough together to prevent the concentration of water and appreciable erosion on the land-slope between the terraces. In the spacing of terraces, however, another important factor must be carefully considered and that is the ability of the terrace-channel to carry away the runoff-water which is delivered to it from the land-slope between the terraces for the most intense rains that are likely to occur. The amount and rate of movement of the water that runs off between the terraces depend upon the nature of the soil, the vegetative cover, the land-slopes, the amount and intensity of the rainfall, and the shape, length, and size of drainage-area.

The ability of a terrace-channel to carry away the runoff-water delivered to it depends upon the shape, the fall, the cross-sectional area, and the frictional resistance to flow. The discharge-capacity of the channel is computed by the formula

$$Q = CA\sqrt{RS}$$

where Q = the discharge in cubic feet per second, C = a coefficient representing the frictional resistance to flow, A = the cross-sectional area in square feet, R = the hydraulic radius depending upon the size and shape of channel, and S = the fall of the bottom of the channel. The results of extensive field and laboratory experiments enable the engineer to determine all of the above factors in computing the discharge-capacity of a terrace-channel. This is particularly important since terrace failures due to exceeding the discharge-capacity of the channel and resulting in the water's overtopping and breaking the terrace are of common occurrence where unscientific guesses have been relied upon instead of fundamentally sound experimental data.

A terrace-channel must not only be able to remove the water from the drainage-area between the terraces but must accomplish this without excessive erosion in the terrace-channel. In other words, it must conduct the water to the terrace-outlet at a low, non-eroding velocity. Both the fall and the shape of the channel can be controlled so as to produce the desired velocity for any particular soil.

A broad, shallow channel will have a lower velocity than a deep, narrow channel. To illustrate, the two channels shown in Figure 6 are capable of removing the same quantity of water from the drainage-area in the same time but the broad, flat channel removes it at a comparatively low velocity of 1.44 feet per second and the narrow, deep channel at a velocity of 2.29 feet per second, a velocity sufficient to cause erosion.

The deep channel has a cross-sectional area of only 12 square feet as compared with a cross-sectional area of 19 square feet for the shallower channel. The shape of the channel alone, due largely to the fact that the line in the cross-section with which the water comes in frictional contact is only 9.4 feet for the deep channel and 26.1 feet for the shallow channel, is responsible for the small deep channel carrying as much water as the large shallow channel.

From the foregoing it has been seen that the control of erosion in a terrace-channel can be accomplished to a limited extent by the shape of the channel. This alone would, of course, not be effective if the fall of the channel were not limited. Results of experiments on the soil-erosion experiment-stations at Guthrie, Oklahoma, and Bethany, Missouri, indicate the effect of fall of broad shallow terrace-channels upon erosion.

The soil-losses in tons per acre during the year 1932 (Fig. 7) at the Bethany Station for terraces with different uniform grades or fall were as follows: Level, 0.63 ton; two inches per 100 feet, 0.95 ton; four inches per 100 feet, 2.91 tons; six inches per 100 feet, 3.32 tons; and eight inches per 100 feet, 7.17 tons. The soil-loss for a terrace with a variable grade of one to four inches was 2.22 tons. Results obtained at the Guthrie Station for terraces with different uniform grades for the year 1932 were as follows: Level, 0.83 ton; two inches per 100 feet, 1.32 tons; four inches per 100 feet, 2.61 tons; and six inches per 100 feet, 2.84 tons.

These results show conclusively that soil-losses from a terraced field increase appreciably with the grade of the terrace, and in order to reduce the losses it is ne-

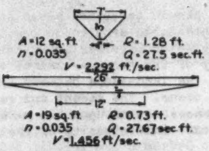

Fig. 6- Comparison of velocities of deep and shallow channels — For fall of 3 inches per 100 ft

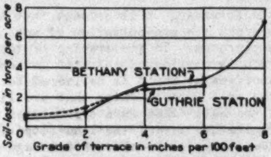

Fig. 7- Curves showing soil-losses from terrace with different grades for year 1932 at Bethany and 1933 at Guthrie

cessary to lower the erosive and silt-carrying capacity of a terrace-channel by limiting the grade and thereby the velocity in the channel. The minimum grade should be used that will be effective in removing the runoff-water from the contributing drainage-area between the terraces which increases with the length of and distance between the terraces. It is believed that in most practical terracing work a grade of four inches per 100 feet need not be exceeded and that satisfactory control can be obtained, from the standpoint of erosive action in channel and silt-carrying power of the water, for grades not exceeding four inches per 100 feet for most types of soils.

Control of erosion in a terrace-channel by vegetation is not practical if the remainder of the field is cultivated since, as has been shown, while vegetation reduces erosion it also reduces the discharge-capacity of the channel which would necessitate the use of an abnormally large channel cross-section to remove the runoff-water. Fortunately when a terraced field is planted to close-growing crops such as oats, the runoff from the field is reduced and the terrace-channel is able to remove the reduced runoff even though its discharge-capacity is reduced by the growth in the channel.

From the foregoing discussion it can readily be seen that considerable ingenuity must be exercised in planning terrace-embankments on different land-slopes so that the cross-sectional area of the channel will be sufficient to take care of the runoff-water, so that appreciable erosion will not occur in the terrace-channel, and so that the shape of the terrace-embankment will not be such as to interfere with the easy operation of machinery in farming the embankments. The type of an embankment will necessarily not be the same on a steep slope of 15 per cent as on a comparatively flat slope of only three per cent, in order to meet satisfactorily the foregoing requirements.

The height of a terrace determines largely the cross-sectional area of the waterway for any particular slope. The higher the terrace, however, the more interference with the operation of farm machinery. If the height of a terrace is kept low in order to meet farm-machinery requirements, this may require reducing the drainage-area by a closer spacing of the terraces in order to prevent the runoff-water from overtopping the low terrace-embankment. Thus it is seen that the interdependence of all factors governing the design of a terrace is such that if a change in any one is made, readjustment of the remaining factors becomes imperative in order to restore the proper balanced relation of the various factors.

The control of erosion in terrace outlet-ditches or gullies is a much more difficult problem than in terrace-channels. The same principles apply, but the general practice of an outlet-ditch carrying the water to the foot of the slope along a natural depression or through an artificial channel often located directly down a slope along a road or a fence results in a large fall in the outlet-ditch.

The velocity in the channel may be reduced somewhat by using a ditch with a broad shallow cross-section, but not sufficiently to prevent erosion. Additional protection against erosion is required by either further reducing the velocity or protecting the channel with a short growth of grass which will not reduce too much the water-carrying capacity of the ditch. Even on moderate slopes it has been found advisable and necessary in most cases to cause an equal distribution of the water across the bottom of the channel by means of planks buried on edge in the ground at close intervals across the channel and with their upper edges about flush with the bottom of the channel. If this is not done there is a tendency for the water to concentrate and cause serious erosion. Also the plank holds the grass in place and checks any small gully-erosion that may start between the planks. This method of control has been found to be quite effective on moderate slopes and for limited drainage-areas as shown in the view which was taken on the Bethany Soil Erosion Experiment Farm near Bethany, Missouri (Fig. 8).

Ditches with large drainage-areas or on steep slopes cannot be very effectively controlled by the foregoing method. Also it is not always possible in all locations to build a broad shallow ditch or in some sections of the country to secure a satisfactory sod in the ditches. Under these circumstances control of the ditch or gully is usually accomplished by means of check-dams built of a variety of temporary or permanent material and so spaced in the ditch that the crest of one dam is about on the same elevation as the foot of the next dam above. The object of spacing the dams in

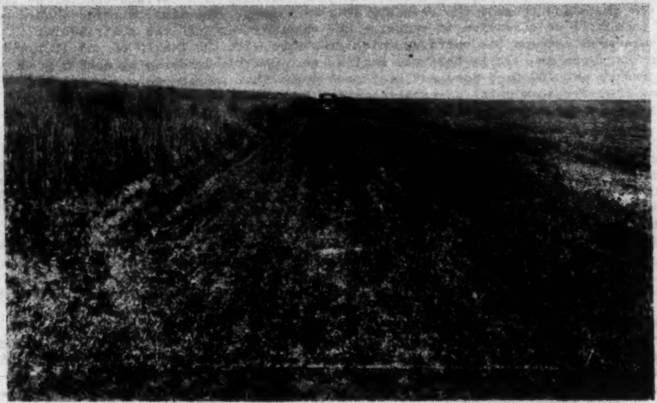

Fig. 8

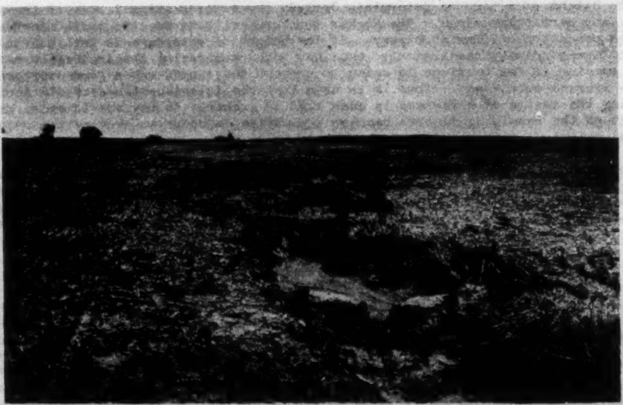

Fig. 9

this manner is to reduce the fall of the ditch between the dams, thereby the velocity and erosive power of the water. The dams are constructed with an apron below to prevent erosive action of the water after dropping over the dam at an appreciable velocity (Fig. 9).

Methods of controlling erosion in runoff-channels such as are required in a comprehensive plan for the control of soil-erosion on agricultural lands are included in the experiments being conducted on the ten soil-erosion experiment farms of the Department of Agriculture established throughout the United States. As time permits, more detailed studies will be made of the dynamics of both erosion and silting in channels which will require studies, observations, and careful field-measurements relating to soils, velocities, channel cross-sections, and frictional resistance to flow.

Bureau of Agricultural Engineering,
U. S. Department of Agriculture, Washington, D. C.

CHARTING THE EFFECTS OF EROSION IN THE OLD PLANTATION-BELT OF THE SOUTHERN PIEDMONT

Glenn L. Fuller

In the spring of 1933, a plan was formulated for investigating the cause of extensive land-abandonment in the lower Piedmont of Georgia, a section of the State comprising some 14 counties, and sometimes referred to as the Old Plantation-Belt. More than 50 per cent of the total number of farms in some of these counties, as recorded in 1920, were abandoned before 1930, according to the Census. This study of the land-conditions was undertaken cooperatively by the Georgia State College of Agriculture, the Georgia Experiment Station, the Southern Forest Experiment Station, the Bureau of Chemistry and Soils, and the Bureau of Agricultural Economics of the United States Department of Agriculture.

A logical step in such a study would have been to make a complete detailed land-use survey of the entire area, but there was not sufficient time. Consequently, five areas of some 8,000 to 10,000 acres each were surveyed in representative locations through the belt. These differed widely as to dominant soil-types. In order to acquire additional information on the distribution of various land-conditions within the region resulting from erosion, a strip was surveyed entirely across the State. This was one-eighth mile wide and 210 miles long, and it traversed the lower Piedmont section from the Savannah River to the Alabama state-line.

It fell to the lot of the writer to organize and carry out the field-work of this survey, with the assistance of A. H. Hasty, of the Bureau of Chemistry and Soils, and of several foresters of the United States Forest Service.

The field-work was carried out jointly, but along two distinct lines of procedure. The soils men classified the soil-types, the degree of slope, and the degree of erosion, while the foresters indicated the land-use classes, which included very detailed delineation of the areas of forest types, pasture, etc., and they also classified the condition of the forests on the various classes of eroded and uneroded soil as shown by the soil-specialists.

Following completion of the field-work, the areas of each soil-type, slope-class, and erosion-class were measured and tabulated, so that correlations could be made. That work is still incomplete. It is expected that it will be finished within the next few months.

The soils specialists were interested primarily in the extent and condition of erosion, its relations to soil-type, degree of slope, vegetation, cultural methods, and ground fires.

The effects of erosion investigated through these surveys related primarily to abnormal or man-induced erosion, as distinguished from the slower normal process of land-denudation going on under natural conditions of cover and ground-structure. This erosion that we are dealing with is strictly man-accelerated erosion.

In these erosion-surveys and related studies, recognition was given to the classification of soil-types as established by the Bureau of Chemistry and Soils. Marked differences in susceptibility to erosion between different soil-types were consistently noted throughout the survey, as was also the fact that differing erosional agencies produced differing characteristic reactions. The only practicable manner of projecting the findings of the erosion-survey to the entire Old Plantation-Belt, was to project the information obtained on each soil-type to the entire area of each type as shown by the soil-maps.

This lower Piedmont section was largely covered by United States soil-surveys made cooperatively by the Department of Agriculture and the State of Georgia, several of which were very old and, in some instances, out of print. On the entire 210-mile survey-strip across the State, however, soil-survey base-maps were used, with the exception of a short strip of about four miles, where the soils were classified during the progress of the erosion-survey.

As previously stated, the large areas to be surveyed were selected with much care, in order that in each instance they would typically represent one or more dominant soil-types. Thus, the area in Jasper County consisted mainly of Davidson clay-loam; the one in Wilkes County was mainly Georgeville clay-loam and very fine sandy loam; that in Monroe County was mainly Cecil clay-loam; the Morgan County area consisted of Cecil sandy loam (mixed phase) principally; while the Meriwether County area comprised a complexity of types, including Appling sandy loam, Cecil sandy loam, Cecil clay-loam, and Davidson clay-loam.

The second correlation of erosion related to surface-slope. This item of the equation was exceedingly variable, but within narrow limits there did not appear any significant variation in erosional activity; hence, after some observation and experimentation, the varying slope-integers were resolved into four classes. Differentiations of classes were definitely established before the survey had progressed beyond the first area. The slopes were divided into A-, B-, C-, and D-groups or classes.

The A-group included all slopes of less than three per cent. It represented the very gently sloping to relatively level soils on which there had been a minimum of erosion under customary method of tillage.

The B-group included those slopes varying from three to seven per cent, and representing the broader classes of land where erosion is always active under cultivation, but on which control-measures can be effectively employed. This group, incidentally, included a large proportion of the tilled land.

The C-group included those slopes ranging from seven to twelve per cent, comprising that class of soils on which it was clearly demonstrable that customary erosion control-measures are insufficient and inadequate where the land is cultivated to clean-tilled crops. This group of soils should be used normally for thick-growing, soil-holding crops, such as grains, grasses, and legumes, or in a farm-system combining the plan of strip-cropping.

The D-group included all slopes of more than twelve per cent, comprising the lands on which erosion obviously can not be adequately controlled under any system of cultivation.

To illustrate the relative extent of these different slope-classes, the total acreages in each class as mapped in the two surveyed areas of Morgan and Jasper counties are given in Table 1.

Table 1--Total areas and percentage uplands for four slope-groups in Morgan and Jasper counties

Class-symbol	Slope	Area		Upland	
		Morgan County	Jasper County	Morgan County	Jasper County
	o/o	acres	acres	o/o	o/o
A	0-3	1468.	1403.5	23.4	17.9
B	3-7	2254.6	4506.2	36.	57.3
C	7-12	1537.6	1752.3	24.6	22.3
D	12 plus	1001.2	199.3	16.	2.5
Totals........		6261.4	7861.3	100.0	100.0

The degree, extent, and character of erosion were shown by symbols. The natural or normal profiles of the different soil-types were carefully examined on representative virgin areas, in order to ascertain by comparative measurements just what soil-loss has been sustained by the lands under cultivation.

Erosion was divided into two major classes: (1) Sheet-erosion and (2) gully-erosion. Sheet-erosion was further divided into four classes, designated by the numerals 1, 2, 3, and 4.

Class 1 includes those soils showing no visible evidence of erosion-loss, such areas occurring usually on the more nearly level stretches of farm-land and meadows, or on virgin areas of timber-lands that have not been subjected to frequent burning.

Class 2 includes those soils from which less than 30 per cent of the A-horizon, in areal extent, has been lost.

Class 3 includes soils from which more than 30 per cent of the A-horizon, in areal extent, has been lost but with frequent traces of it still in place.

Class 4 included those areas from which all the A-horizom had been lost, with even some areas from which the B-horizon has been removed, thus exposing the raw, non-productive C-horizon.

On this survey, gullies were not defined as such unless they had penetrated into the B-horizon. Small incipient gullies, occurring entirely within the A-horizon, were considered merely as a phase of severe sheet-erosion, for the reason that they would be obliterated by tillage and could be controlled by practiced measures.

The severity of gullying was expressed in two classes: (1) One designated by (5) indicating gullied lands of agricultural value, and mapped in conjunction with sheet-erosion classes 2, 3, or 4, as the case might be, and (2) one designated by (6) indicating lands so badly gullied that they are no longer capable of any practical agricultural usage.

The different horizons of weathered or disintegrated soil-material over this crystalline Piedmont country react so differently to the same erosional agencies that it appeared of great importance to indicate the depth of gullies. Relatively shallow gullies within the compact B-horizon invariably have V-shaped sides and they are readily susceptible to definite stabilization or even to complete correction. However, if the gully has penetrated through the B-horizon into the C-horizon it becomes U-shaped, constantly and rapidly growing in size through the easy and ready washing of the loose, disintegrated C-material and the constant undermining of the more compact B-horizon, allowing it to cave in. Thus these gullies eat their way up the slopes and widen their channels as they go, constituting a great destroying menace. Such gullies are indicated by a symbol "V" following the regular gully symbol-number.

It was necessary to know not only the degree and extent of erosion, but to what extent it had been effectively stabilized or controlled by volunteer or planted cover, and also under what conditions and where active erosion occurred in forested areas. Therefore, on areas where any type of erosion had been arrested, designation was made by underscoring that erosion-class.

Thus, the cultural survey indicated the type of cover and its effectiveness, as well as the frequency and effect of fires, while the erosion-survey showed the character and extent of erosion. It was observed over the wooded areas that severe burning tended to induce gullying rather than sheet-erosion, while burning or over-grazing of grass-lands tended to induce sheet-washing rather than gullying, although gullying might or might not be present in such cases.

It was also determined that very little virgin soil remains in this Old Plantation-Belt. Practically all the wooded land once had been under cultivation, some of it cleared more than a hundred years ago, and some worn out and abandoned fully a hundred years ago. Where erosion had been most active in removing the topsoil and in gullying the slopes, it was found that a very long period of time elapsed after abandonment before the native vegetative growth could stabilize all forms of erosion. The indications are, in many cases, that 75 to 100 years were required. Where the gullies were very deep, they were rarely stabilized by vegetation at all, but continued to expand and progress in their ruthless march, engulfing trees along their course and destroying good farm-lands as they ate their way higher and higher into the agricultural slopes.

The technique of coordinating the field-survey of soils, slope- and erosion-conditions, consisted of mapping the soil-types, then indicating definitely classified slope-groups, with finally each slope-group divided into definite erosion-classes.

Time does not permit the presentation of the full details relating to the findings of the surveys. I have endeavored to present the methods by which the survey was made. However, it would perhaps be of interest to present some of the major results from a single area in Jasper County. Data are not available yet from the strip-survey nor from the areal surveys of Wilkes, Meriwether, or Monroe counties.

In making the percentage-determinations for all the factors hereafter mentioned, only the upland is considered. Each slope- or erosion-class is shown by percentage of the total upland-area, the bottom-lands being arbitrarily excluded because it was felt that more accurate values would be obtained if only upland figures were used.

The areas and percentages of the different erosion-classes, irrespective of slope- or soil-type, for the 7861.3 acres surveyed in Jasper County are shown by Table 2.

Table 2--Distribution of erosion-classes in Jasper County

Erosion-class	Area	Upland-area
	acres	o/o
1	51.4	0.7
2	1884.4	24.0
3	1646.2	20.9
4	178.2	2.3
2(5)	83.8	1.0
3(5)	1983.8	25.2
4(5)	1941.9	24.7
(6)	91.6	1.2
Totals	7861.3	100.0

Table 2 shows that only 51.4 acres or 0.7 per cent of the upland-area showed no erosion, 47.9 per cent of the area was not gullied, while 52.1 per cent was gullied, 25.7 per cent of the area had lost less than 30 per cent of the A-horizon, as compared with 74.3 per cent which had lost more than 30 per cent of the A-horizon, and 28.2 per cent of the total area had lost all the A-horizon. Although 52.1 per cent of the area was gullied, only 1.2 per cent of the area was completely destroyed by gullying. This was a lower percentage than in Morgan County where 4.6 per cent of the upland-area was destroyed and it is believed that percentage will be materially higher in some of the other areas, for which figures are not yet available.

As was expected, there was very close correlation between the different slope-groups and the erosion-classes. The percentage of each erosion-class which occurred on the different slope-groups was found as shown by Table 3.

Table 3--Percentage of each erosion-class on the different slope-groups in Jasper County

Slope-group	Erosion-class							
	1	2	3	4	2(5)	3(5)	4(5)	(6)
	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o
A	18.9	45.6	28.5	36.7	....	....	....	....
B	0.0	38.6	64.8	55.2	34.6	81.3	49.6	8.1
C	56.4	15.3	6.7	8.1	53.5	18.7	44.5	33.9
D	24.7	0.5	....	....	11.9	....	5.9	58.0
Totals	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Perhaps the relationship is more clearly shown by inverting Table 3 to show the percentage of each slope in the different erosion-classes as indicated in Table 4.

Table 4--Percentage of each slope-group in the different erosion-classes in Jasper County

Erosion-class	Slope-group			
	A	B	C	D
	o/o	o/o	o/o	o/o
1	0.7	....	1.6	6.4
2	61.2	16.1	16.4	4.7
3	33.4	23.7	6.3	...
4	4.7	2.2	0.8	...
2(5)	....	0.6	2.6	5.0
3(5)	....	35.8	21.2	0.0
4(5)	....	21.4	49.3	57.3
(6)	....	0.2	1.8	26.6
Totals	100.0	100.0	100.0	100.0

On this particular area of 7861.3 acres in Jasper County, 6465.2 acres or 82.2 per cent of the total area was Davidson clay-loam, the balance consisting of 973 acres of Cecil clay-loam, 115.6 acres of Cecil sandy loam, and 307.5 acres of Cecil sandy loam--mixed phase. This last soil-class is a partially eroded phase of Cecil sandy loam. While the areas of the soils other than Davidson on this particular area are too small to be of great significance, their distribution into the different erosion-classes is indicative of their trend. Therefore, they are included with the Davidson in Table 5 showing the extent of erosion by soil-type.

Table 5--Distribution of each soil-type in the different erosion-classes in Jasper County

Erosion-class	Soil-type			
	Cecil clay-loam	Cecil sandy loam	Cecil sandy loam (mixed phase)	Davidson clay-loam
	o/o	o/o	o/o	o/o
1	0.6	100.0	37.1	0.7
2	23.4	.....	19.5	22.1
3	15.4	.....	....	22.2
4	2.0	.....	....	2.5
2(5)	1.1	.....	....	1.1
3(5)	30.0	.....	39.9	24.3
4(5)	27.5	.....	3.5	25.7
(6)	....	.....	....	1.4
Totals	100.0	100.0	100.0	100.0

The prevalence of gullying on the different types was significant also, as shown by Table 6.

Table 6--Percentage of each soil-type gullied and non-gullied in Jasper County

Erosion			Soil-type			
Character	Area	Part	Cecil clay-loam	Cecil sandy loam	Cecil sandy loam (mixed phase)	Davidson clay-loam
	acres	o/o	o/o	o/o	o/o	o/o
Gullied	3760.2	47.8	41.4	100.0	56.6	47.4
Non-gullied	4101.1	52.2	58.6	.....	43.4	52.6
Totals	7861.3	100.0	100.0	100.0	100.0	100.0

The figures showing the extent to which erosion had been stabilized are incomplete due to lack of the tabulated planimeter-figures for the land-cover. However, the figures showing the percentage of the different erosion-classes which were found to be stabilized are complete as shown in Table 7 even though the conditions which caused stabilization are not tabulated.

Table 7--Percentage of erosion-classes arrested in Jasper County

Erosion-class	Area	Active	Arrested	Partly arrested
	acres	o/o	o/o	o/o
1	51.4	....	100.0	...
2	1884.4	85.1	14.9	...
3	1646.2	85.0	15.0	...
4	178.2	100.0	....	...
2(5)	83.8	51.1	48.9	...
2(5)V	0.0	....	....	...
3(5)	1934.5	79.7	15.7	4.6
3(5)V	49.3	100.0	....	...
4(5)	1631.2	87.3	7.9	4.8
4(5)V	310.7	84.4	15.6	...
(6)	91.6	100.0	....	...
Totals	7861.3	83.9	14.0	2.1

[Note--The partly-arrested grouping refers to the combined gully- and sheet-erosion classes where one was stabilized while the other remained active. This occurred usually in reforested areas where sheet-erosion had become stabilized but gullies remained active, especially if the gullies were deep. Space does not permit giving this information for each soil-type.]

It may be of interest to give the percentage of the gully-classes which were deep gullies. As previously stated, gully-depth was classified according to penetration into the C-horizon. Of the total area of erosion-class 2(5), that class having moderate gullying but where less than 30 per cent of the A-horizon had been lost, none of the gullies was deep. On the 3(5) class where more than 30 per cent but not all of the A-horizon had been lost, only 2.5per cent of the area had deep gullies, 49.3 acres out of 1983.8 acres. However, in the 4(5) class, where all the A-horizon had been lost, 310.7 acres out of 1941.9 acres, or 16 per cent of the class, was in deep gullies.

No gullies were found on Cecil sandy loam and no deep gullies were found on Cecil sandy loam - mixed phase. On Cecil clay-loam 7.1 per cent of the gullied area was classed as deep gullies as compared to 12.1 per cent of the Davidson clay-loam so classed. However, the inequality of the areas of these two soil-types minimizes the significant value of that comparison.

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THE CHOKING OF PORE-SPACE IN THE SOIL AND ITS RELATION TO RUNOFF AND EROSION

B. H. Hendrickson

The identification and evaluation of all factors influencing runoff and erosion on the erosive lands of the nation are manifestly studies of the most fundamental importance, especially in so far as they may be made to yield definite information upon methods of control over this insidious tendency upon cultivated lands.

Investigations in progress at our Soil Erosion Experiment Stations have rather clearly shown that we may divide the factors that are mainly responsible for preventing or provoking erosion into two broad categories, namely: (1) The protective effects of dense covers of vegetation of one kind or another, and (2) the almost certain destruction that follows the exposure of cultivated slopes to natural conditions of rainfall. Thus it is a fact that increasing the slope on Kirvin fine sandy loam-soil--which is the most extensive and probably the most erosive soil-type in the East Texas-Louisiana-Arkansas sandy-land region served by the Erosion Station at Tyler, Texas--from 8 3/4 per cent to 16 1/2 per cent does not appreciably affect the almost perfect erosion-control provided by the use of a dense Bermuda sod. However, under conditions of clean cultivation, as with cotton, the same change in slope on the same soil greatly increases the soil-loss which already is excessive under such conditions on slopes of more than six or seven per cent.

Since erosion is a natural consequence of runoff, the first logical question that might be asked is why runoff occurs under given conditions of slope and surface-exposure. The simplest answer is, of course, because the rate of rainfall exceeds the rate of infiltration or penetration of water into the soil. The capacity of a soil for taking up water and the rate at which it can do it thus become important factors for consideration along with the physical laws governing these tendencies.

When falling raindrops strike soil-surfaces which are unprotected by a littered forest-floor or by dense covers of vegetation, as grass, the water tends immediately to become muddied by fine material thrown forcibly into suspension. It had been pointed out by Lowdermilk and Bennett (H. H. Bennett, Some comparisons of the properties of humid-tropical and humid-temperate American soils, Soil Sci., v. 21, No. 5, May 1926, and W. C. Lowdermilk, Influence of forest-litter on runoff, percolation, and erosion, J. Forestry, v. 38, No. 4, 1930) that such fine soil-material in suspension tends to clog the pores of the soil and thus appreciably increase runoff. In order to investigate this point some simple, preliminary experiments were carried out. These studies are referred to and the results summarized briefly in the paragraphs that follow.

Laboratory experiments

In order to study the effect of applications of silt- and clay-suspensions to tops of columns of sand on the rate of infiltration of water, three glass tubes two inches in diameter and 14 inches long were set up and filled uniformly to within one-half inch of their tops with screened sand.

Procedure--One inch of clear water was slowly added to the column designated as a check. To the other two were added respectively a similar volume of soil-suspension made up in the proportion of 60 grams of fine material to 500 cc of clear water of Bowie silty sludge and Kirvin clayey sludge. This proportion of soil and water was used as representing heavy wash. In one instance the soil-material used was a sludge of Bowie silt-loam and in the other a sludge of the clay-subsoil of the Kirvin fine sandy loam. After the first free water had disappeared into the sand, then six inches of clear water were added slowly to each column. The time required for infiltration to specified depths in the columns was noted.

Results--In both cases where suspensions were used, the fine materials settled quickly in the form of a thin film about one-sixteenth inch thick on the top of the sand-column and remained practically intact. Following the application of six inches of clear water it required three times as long for infiltering water to reach the four-inch depth when the silty suspension was applied and eight times as long when the clay-suspension was used, as compared in either case with the check. At the eight-inch depth, the corresponding time-ratio, as between clear water, silt-suspension, and clay-suspension, was 1:3.5:7.5; at the 13-inch depth it was 1:4:8. The actual time consumed in seconds for the check column was as follows: Four-inch depth, 21 seconds; eight-inch depth, 60 seconds; 13-inch depth, 109 seconds.

Discussion--The pore-clogging effect of the thin films of sludge on the tops of the sand-columns thus seemed to vary consistently with the texture of the materials used. If the fine materials had been appreciably removed by downward infiltering water, the infiltration-ratios at the different depths would have changed markedly. Since this was not the case, no mechanical analyses of the topsoil of the sand-columns were made after the experiment had been run. As a matter of fact, only a visible trace of whitish silty sludge appeared at depths of one-sixteenth to one-quarter inch below the surface of one sand-column, and of red clay in the other. Thus, effective downward translocation of the clogging surface-layers did not occur. In this connection, it appears that the packing together of the silt, and the packing and sticking together of the clay-particles were about equal so far as resistance to movement by infiltering water is concerned.

Other laboratory tests and summary--Certain other generally similar studies were made later to determine what quantities of water applied following the surface-deposition of material of varying textures on the tops of the sand-columns would be required to wash them into the sand beneath. It was found that as much as 27 inches of clear water, the equivalent of about three-quarters of the mean annual rainfall, could be applied without any indication of effect from this standpoint.

From these preliminary studies in the laboratory it appears that even very thin layers of silt- and clay-sediments applied in suspensions quickly "blanket" flat sand-surfaces and effectively clog the pores in such a way as seriously to impede the movement of water into the soil-body when applied at the surface.

Controlled plot-experiments

Following these preliminary studies in the laboratory a somewhat different approach was made to the subject by setting up controlled plots in the open on Kirvin fine sandy loam. These plots were three feet wide, ten feet long, and had a natural slope of 8 3/4 per cent. They were set up for the purpose of studying the effect of artificially "muddied" water applied as rain to the upper end of the slope upon the resulting runoff and erosion. The soil was in a dry, loose fallow condition at the time of the first trial.

Test 1 procedure--Water was applied only at the upper ends of the plots by means of a sprinkler attached to a hose leading from a supply in an iron barrel. It was passed through a strip of wire screening of one-sixteenth inch mesh on which the dry sifted soil-materials were added gradually to the stream.

On the first run Plot 1 received clear water only, Plot 2 received the same volume of water plus four pounds of Kirvin fine sandy loam topsoil, and Plot 3 received four pounds screened Kirvin clay in a dry, powdery condition. One inch of water was used for the first run on all plots and the test was repeated about half an hour later. The proportions of water and soil or sediment were those of "light sheet-wash."

Results--The results of the first two trials referred to above are to be found in Table 1, where individual and average values are given as rates of "rainfall" supplied, per cent runoff that resulted, and the soil lost in tons per acre.

Table 1--The effect of suspended soil-materials on runoff and erosional losses when applied with artificial rain to a natural slope of Kirvin fine sandy loam

Materials used	Test-runs	One inch applied in	Runoff	Erosion	
		minutes	o/o	pounds	tons per acre
Clear water	1	12	None	None	.....
	2	11 1/4	9.95	3.83	.....
Average	--	11 5/8	4.97	1.92	0.001
Water and sand	1	11	3.56	5.61	.....
	2	15	10.02	6.57	.....
Average	--	13	6.79	6.09	0.003
Water and clay	1	14	0.01	trace	trace
	2	12	17.80	2820.00	1.410
Average	--	13	8.91	1410.00	0.705

Discussion--For the first run, both the sand and clay added to the clear water deposited readily and was plainly visible on the upper halves of the plots. The rates of water-application varied somewhat due to slight stoppages in the sprinkler-nozzle. In the first run, the rate applied was non-erosive to just barely erosive. On the clear-water plot, the water applied did not quite reach the lower end.

For the second run, a half hour later, approximately the same rate of water-application caused runoff varying from 9.95 to 17.80 per cent, the maximum figure being obtained from the plot receiving water plus clay. This time the red-clay sheet covered the plot completely, checked infiltration, and induced runoff to such a surprising extent that 1.41 tons per acre of erosion resulted, along with the highest runoff-figure. Neither of the two other plots eroded appreciably.

From these results it would appear that runoff-waters carrying relatively small loads of fine sediment in suspension under sheet-erosion conditions, on a representative slope of loose, fallow Kirvin fine sandy loam, can be expected to increase erosion-losses enormously from moderately erosive rains.

Test 2, natural rain--A week later, after the soil had become dried and surface-crusted in the prevailing hot summer weather, a slightly erosive, natural rain fell on these same small test-plots, with the results shown in Table 2.

Table 2--Runoff and erosion on small test-plots following natural rain of 0.78 inch* one week after the completion of the preliminary tests

Plot	Runoff	Erosion
	o/o	tons per acre
1--Clear water	27.4	0.421
2--Water plus sand	27.4	0.567
3--Water plus clay	41.1	1.081

*Rain of July 15, 1933, 0.70 inch in 40 minutes causing runoff.

This rain was not erosive on an adjoining set of plots, excepting for those in surface-crusted condition, which produced small runoff with little erosion. The little test-plots had received applications totaling two inches of water only a week previous and the soil was thus in a more moist condition. In Table 2 it is seen that the sand added to Plot 2 had only a slight effect on erosion and none on runoff, as compared with the check. Both the runoff- and erosion-losses from Plot 3, which has a thin dry crust of red clay on its surface, were considerably higher than from the other two plots. The fact that natural erosion was not enormously increased by the presence of the red clay (as it was during the second run, previous) would seem to indicate that the pelting force of the large drops of rain broke up the clay-crust and caused much of it to be washed off the plot. The washoff from this plot contained a great amount of clay in suspension and was decidedly red in color. There was indicated, too, a sufficient, pore-clogging by the clay through its mere presence on the surface to cause a doubled erosion-loss from a slightly erosive rain.

Test 3 procedure--Another test-run was made on these same plots a month later, at which time the rate of water-application was double that used in the previous treatment, and the proportion of sediment in suspension raised to that of "medium sheet-wash" (two inches of water in about ten minutes; 16 pounds of soil-material added per plot--except on check).

In this second test, as in the first, the water was applied as a continuous flow at the upper ends of the plots, with the use of a somewhat larger nozzle. Plot 1, the check, received clear water only; Plot 2 received an additional treatment of 16 pounds of Kirvin fine sandy loam; Plot 3 received an additional treatment of 16 pounds of Kirvin clay. As before, the soil-materials were sifted at a regular rate on the spreading screen through which the water passed before falling on the soil-surface.

Results--The results of this third study are rather fully indicated in Tables 3 and 4. In Table 3 the rate of rainfall, per cent runoff, and erosion-losses are tabulated, while in Table 4 is to be found information upon the approximate mechanical composition of the materials washed off the plots during this test.

Table 3--The effect of increasing quantities of suspended soil-materials upon runoff and erosional losses when applied with artificial rain to a natural slope of Kirvin fine sandy loam

Plot	Application		Runoff	Erosion	Per cent washoff (silt plus clay)
	Material	2 inches in			
		minutes	o/o	tons per acre	o/o
1	Water	10 1/4	54.9	0.17	83.5
2	Water plus sand	9 1/4	55.9	3.55	57.9
3	Water plus clay	9 1/4	53.0	9.44	49.8

Table 4--Approximate mechanical composition of washoff from plots upon natural slope of Kirvin fine sandy loam during third test

Plot	Washoff		
	Sands	Silt and clay	Total
	pounds per plot	pounds per plot	pounds per plot
1	0.04	0.20	0.24
2	2.09	2.89	4.96
3	6.63	6.56	13.19

The variation in runoff from 53.0 to 55.9 per cent for the three plots is not considered significant. Ordinarily a runoff of 50 per cent indicates severely erosive conditions, amount and rate of rainfall being, of course, important considerations.

So far as erosion-losses are concerned, Plot 1, to which clear water only was added, lost only 0.17 ton per acre, with no gullying nor evidence of sedimentation on the surface of the soil. The addition of 16 pounds of Kirvin fine sandy loam-material to Plot 2, however, caused an erosion-loss of 3.55 tons per acre, an amount 21 times greater than that obtained from the check. It is interesting to note that, although 16 pounds of sandy sludge had been applied, only 4.96 pounds of total washoff resulted. Gullies formed on the whole plot, top to bottom, but those on the lower half of the plot refilled with sandy sediment during the close of the run. It is also interesting to note that the washoff from this plot contained 57.9 per cent material finer than sand. This figure indicates twice as much fine material as the composition of typical Kirvin topsoil. Nearly all of the sand applied remained on the plot, the erosion-process in this instance tending to remove the finer materials both from the mixture applied and the surface-soil of the plot and to deposit the sand. In the case of Plot 3, the addition of 16 pounds of clay caused a loss of 9.44 tons per acre, which is 55 times greater than that obtained from the check. Only 13.19 pounds of total washoff resulted, however, although 16 pounds of clay had been added. Gullies formed on the whole plot, top to bottom, but these did not tend to fill. On the contrary, they continued to deepen as erosion progressed. The washoff from this plot was 49.8 per cent sand, which shows that half of the clay remained on the plot.

Summary of plot-experiments

The high resistance to erosion shown by Plot 1, to which clear water only had been added, does not mean that the amount and rate were insufficient to produce severe erosion in Nature. It must be remembered that the water was not applied as rain over the whole of the plots, but only at the upper ends, and that the plot-lengths were only ten feet, thus not affording opportunity for much acceleration of the runoff. There was also but little of the pelting effect of raindrops on loose soil, as occurs in Nature during torrential rains. The comparatively high absorptive rate, or infiltration-rate, of soil in loose tilth, when clear or very nearly clear water runs over the surface as thin sheet-wash, is very apparent from this experiment. Under comparable conditions, sandy material in suspension was deposited, forcing a considerable erosion-loss of the finer, fertility-carrying soil-materials. The clay applied in suspension blanketed the surface of the soil on Plot 3, checked normal infiltration, and induced runoff very quickly, which formed deep gullies. The fact that clay-particles did not perceptibly adhere to gully-sides and gully-bottoms must have permitted a good rate of infiltration in these eroding zones, since the total percentage of runoff from this plot was less than from the other two plots.

On the whole, it would appear from these studies that the following principles are highly important in erosion-control:

(1) Keep the soil in the highest possible state of permeability.

(2) Guard this condition just as far as possible, as with vegetation-covers, against the beating effects of rain which tends to throw the soil-material into suspension and so clog the natural porosity of the soil as the water tries to enter.

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ACCELERATION OF EROSION ABOVE GEOLOGIC NORMS

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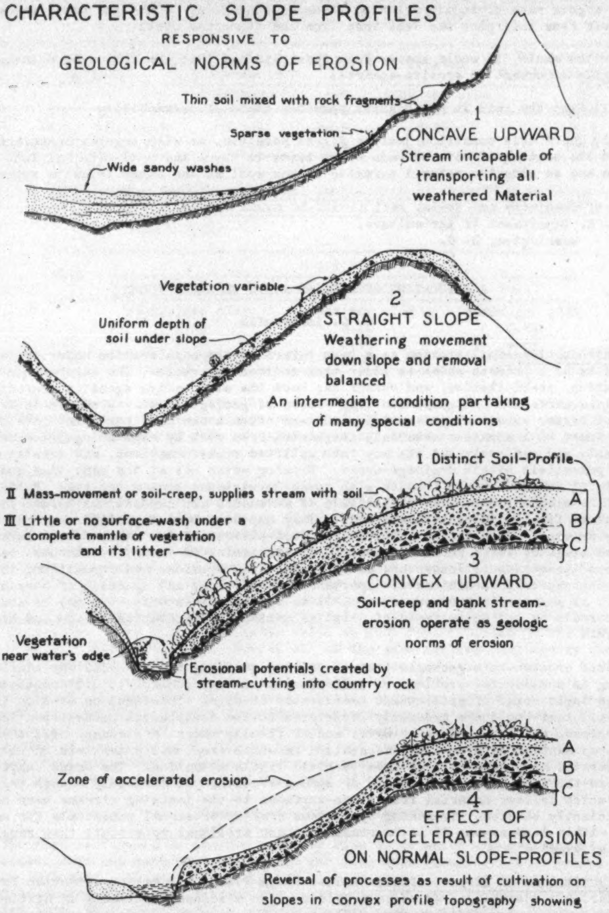
Introduction--Soil-erosion as a term refers to the acceleration under certain conditions of a process which is older than sedimentary rocks. The water-cycle of evaporation, precipitation, and runoff has been the most active agent in degrading major land-surfaces throughout the long record of geologic time. Wind has in arid regions of lesser extent played an important and often a dominant part; but flowing water, armed with abrasive materials fragmented from rock by weathering processes, has tirelessly and endlessly cut its way into uplifted rock-formations, and created erosional potentials within drainage-areas. Flowing water has at the same time swept the products of denudation and erosion with equal persistence toward the sea. Products of erosion have undergone a wide vicissitude of movements and depositions before finding their place finally in sedimentary beds. They may have been deposited many times on the way as shoal banks and as alluvium on flood-plains and in valley-fills, later to be moved stage by stage further seaward. Closed basins of inland continental regions have been the scenes of lesser cycles of denudation, erosion, and deposition, in which occur special conditions of importance in hydrology and dynamics of stream-action. As a geologic process, erosion is as old as rain-storms, but may be accelerated in soils by baring surfaces of pristine mantles of vegetation by man and his agencies.

Since erosion is a geologic process of long standing it is useful for clarity of thinking in considering problems of soil-erosion and its control to differentiate between geologic norms of erosion and accelerated erosion. Treatises on erosion in geological text-books are generally restricted to the conspicuous processes evident in arid regions, and to the work of waves and of flowing water in streams. Responses in landscapes mantled with soil and vegetation in which erosional potentials on slopes are generated by stream-cutting have received little attention. The Grand Canyon stands as the example par excellence of stream-erosion, yet strangely enough the forces which deliver material from slope-surfaces to the incising streams have been insufficiently studied. Trenching by streams creates erosional potentials for water-action within landscapes; it is response to these erosional potentials that requires our brief examination.

Significance of slope-profiles--Walter Penck (1923) has called attention to three characteristic assemblages of slope-profiles which disclose resultants of distinctive processes over long periods of time. Slope-profiles may be either concave, convex upward, or straight. Straight slopes represent intermediate responses. The concave and the convex slopes are essentially responses to different climates with corresponding influences of characteristic vegetation. Shaler (1905), one of the earliest students to perceive the nature of the processes of soil-erosion, suggested that annual precipitation of 20 inches marked this climatic division. With rainfall less than 20 inches in temperate climates, streams are generally incapable of sweeping out of their valleys the detrital products of weathering on slopes. Soils on slopes are

FIG 1

CHARACTERISTIC SLOPE PROFILES
RESPONSIVE TO
GEOLOGICAL NORMS OF EROSION


Thin soil mixed with rock fragments
1
Sparse vegetation
CONCAVE UPWARD
Stream incapable of transporting all weathered Material
Wide sandy washes
Vegetation variable
2
STRAIGHT SLOPE
Weathering movement down slope and removal balanced
An intermediate condition partaking of many special conditions
Uniform depth of soil under slope
I Distinct Soil-Profile
II Mass-movement or soil-creep, supplies stream with soil
III Little or no surface-wash under a complete mantle of vegetation and its litter
A
B
C
3
CONVEX UPWARD
Soil-creep and bank stream-erosion operate as geologic norms of erosion
Vegetation near water's edge
Erosional potentials created by stream-cutting into country rock
A
B
C
Zone of accelerated erosion
4
EFFECT OF ACCELERATED EROSION ON NORMAL SLOPE-PROFILES
Reversal of processes as result of cultivation on slopes in convex profile topography showing typical convex profiles under vegetation and concave under cultivation

thin, with little or no profile-development, and valleys are filled with detrital material. This condition produces a characteristic slope-profile which is concave upward, typical of arid regions. Scantiness of vegetation on slopes and of surface-control, as a response to low rainfall, further accentuates the rapid removal of products of weathering down slopes, as is shown in the soil-profiles of arid regions (Fig.

1). Immaturity of slope soil-profiles in such regions is further evidence of relatively rapid movement of material from the upper slopes.

Straight profiles of slopes within landscapes represent an intermediate position, where removal occurs as rapidly as weathering provides material, and generally approach in gradient the angle of repose of fragmented material. The concave types of slopes are responses to erosional potentials which represent geologic norms of erosion within arid regions. Except in special cases, acceleration of erosion from slope-surfaces within arid regions does not develop to the extent found in regions of convex slopes, to which our attention is chiefly directed in this paper.

In regions where the characteristic slope-profile is convex upward certain definite problems arise under cultivation and use of land. Such regions enjoy an annual rainfall sufficient to support a more or less complete mantle of vegetation, whose protection has given rise to a considerable accumulation of soil. Moreover, drainage-streams are amply supplied with flows capable of removing products of weathering. Topographically, such regions are characteristically rounded in outline; hills are round-topped and grass- or forest-clad. Slopes steepen toward the drainage-channel as shown in Figure 1. The Piedmont region of the Atlantic seaboard may be cited as a typical example of the well-developed responses of topographic form under mantles of vegetation to erosional potentials generated by incision of streams.

Geologic norms of erosion within such regions have received inadequate attention. It is useful in studies of erosion-control to visualize the manner in which norms of geologic erosion take place under a completely mantled landscape of rounded topography. Coverage of vegetation and its layer of ground-litter under pristine conditions render surface-wash of soil negligible, as may be concluded from experimental studies by the writer and others (1930). Weathering by solution proceeds very slowly to degrade land-surfaces except under exceptional conditions. Soil-creep, however, makes the principal contribution of material to incising streams. Sauer (1934) has referred to this process as mass-movement of soil.

Soil-creep--Such soil-creep or mass-movement is generated by stream-cutting, which creates erosional potentials by rendering stream-banks more steep, and by undercutting. Bank-erosion thus removes the material delivered down slopes by soil-creep (Fig. 1). The soil-mass moves with glacier-like slowness down slope at varying rates by layers. The finer the texture of soil, the more rapid will such movements be on slopes of equal gradient under the same moisture-supplies.

On gentle slopes within humid to semi-arid regions, soil formational processes may proceed more rapidly than soil-creep, and thereby have time to develop distinct soil-profiles. On steeper slopes of residual soils, moreover, soil-creep may proceed rapidly enough to interfere with profile-development; and on quite steep slopes, creep may bring fragmented rock from the weathered C-horizon to the surface. Fragments of country rock throughout profiles of residual soils on slopes are indications of comparatively rapid soil-creep toward drainage-channels.

Importance of relict areas in erosion-studies--In examining the operation of accelerated erosion it is well to begin investigations with natural undisturbed conditions of landscapes. Relicts of primeval vegetation and soil-profiles facilitate comparative studies. Where, however, no relicts are extant, difficulties and uncertainties surround reconstruction of rates of normal processes. Assuredly the most reliable device in the second case is to set aside areas protected from all major artificial influences, such as use or destruction of natural vegetation, be it timber or grass, by grazing, trampling, lumbering, clearing, and cultivation. In such areas natural vegetative succession will give within a few years a more accurate expression of the potentialities of control of runoff and erosion of soil, and other factors under prevailing climate than any other contrivance. Moreover soil-profiles will not be so quickly restored, for soil formational processes proceed at a much slower rate than vegetative succession. Norms of processes under conditions undisturbed by human or artificial agencies or their nearest approximations represent most stable natural conditions and are required for comparative studies of soil-erosion.

Interdependence of vegetation and soil--Soil-coatings of a landscape under humid to semi-arid climates are the product of processes of weathering of the original rock-material, influenced by climate and slope, through time, under controls of a mantle of vegetation. Vegetation plays a remarkable rôle (Glinka, 1927, p. 8); it accelerates weathering; it supplies nutrients for myriads of soil micro-flora and fauna, and for burrowing animals (Grimmet, 1926, and Feher, 1929); it, in turn, prevents rapid soil-wash by favoring percolation of rain-water, and by protecting soil-surfaces from erosive action of wind and flowing water; in favoring accumulation of a thick coating of soil it again tends to retard rates of weathering of underlying rock (Shaler, 1891). On the other hand, vegetation is unable to develop to its climax without deep soil to serve trifold functions of growing site, of nutrient supplies, and of water-storage as field-capacity moisture at the disposal of plant-formations. A remarkable dependence of long standing exists between soils on convex slopes and their natural vegetation. Development of soil and vegetation has progressed dependently through periods of time often to be measured in geological terms.

The soil-coating is at the same time subjected to erosional processes whose operations are reflected in sculpturing of landscapes. Erosional potentials are produced principally by gradients of land-uplift and by trenching of streams. Under natural conditions within climatic regions supporting complete coverage of vegetation, the soil-coating is subjected to the operation of erosional potentials under vegetative restraints. Topographic form in slope-profiles as previously indicated represents the operation of erosional processes generated by potentials under restraining influences of natural mantles of vegetation responsive to climate. Erosion under these natural conditions has been designated a "geologic norm of erosion" by the writer (1931); McGee (1891, p. 445) refers to this concept as "old erosion." More recently the concept is less concisely designated "normal erosion."

Geologic norms of erosion--The geologic norm of erosion as a concept is not a uniform phenomenon. It responds to varying supplies, intensities, and characters of precipitation as affected by temperatures, to faulting and geological structures, to landslides, and to entrenching of streams. It represents inevitable processes of degradation and planation of land-forms above sea-level measured in geological time-units. Geologic norms of erosion may be considered both as limits of practical measures of erosion-control and as a basis for measurement of acceleration of soil-erosion.

Accelerated erosion--Acceleration of erosion above geologic norms is a second important concept. It represents augmented processes of wind- and water-erosion under erosional potentials caused by the removal of controls exercised by a mantle of vegetation. Destruction of native mantles of vegetation may be caused by fire, destructive lumbering, heavy grazing, by smelter-fumes, by railraod and highway cuts, and by clearing and cultivation for agricultural crops. Perhaps the earliest reference to processes of accelerated erosion is found in Isaiah 7:23-25. Marsh (1907) and more recently Turrill (1929), the writer (1926), Bennett and Chapline (1928), and others, have indicated the effects of destruction of coverage of natural vegetation on accelerating erosion.

Accelerated erosion within convex slope-profile topography occurs as surface soil-wash which studies by Bennett (1934) have shown to occur on cultivated fields at a stupendous rate in comparison with surface removal under a complete cover of vegetation, such as grasses and cover-crops. Surface soil-wash or "soil-erosion" immediately sets in motion processes which tend to produce a concave slope-profile, as designated in Figure $1_{(4)}$. The loss of vegetative control on slopes through fire has been found in the writer's studies (1934) to be important in accelerating surficial runoff and in the corresponding soil-erosion from non-agricultural soils.

Summary--Differences between geologic norms and accelerated erosion are of vital importance in national economy. Such differences affect rates of soil-removal in relation to processes of soil-formation. Soils are rarely destroyed by erosion of geologic norms, or normal erosion. Accelerated erosion on the contrary proceeds at rates greater than soil-formation, truncates soil-profiles and in time destroys the soil. Degree of acceleration depends on continued mismanagement of land. In areas, however, where delicate balances exist between vegetative control and erosional potentials, acceleration of erosion may proceed without natural check until utility of soil-resources is seriously impaired or vanishes, and give rise to suicidal agriculture. Artificial aids to control then become necessary to bring into full play forces of natural control.

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STILL FURTHER STUDIES ON ABSORPTION OF RAINFALL IN ITS RELATIONS TO SURFICIAL RUNOFF AND EROSION

W. C. Lowdermilk and P. B. Rowe

Introduction--The studies begun in China by the senior author in 1924 and reported in other papers (1926, 1929, 1930) have been continued in California. Conclusions from these studies have indicated that forest-covered soils are more absorptive of rain than soils bared of all vegetation and, further, that the layer of forest-litter is the most important part of a mantle of vegetation in maintaining a soil-profile at its maximum rate of percolation. The principal function of forest-litter was found not to be its capacity for absorption of water, the oft-cited "sponge effect", but its rôle in keeping surficial water clear and the prevention of sealing the soil-surface, a condition which maintains soil-profiles at maximum capacities for absorption. Baring of the soil by clearing and cultivation was found in China to be responsible for important increases in rates of surficial runoff and erosion as compared with those from undisturbed surfaces of natural mantles of vegetation. Temple forests which have been preserved since time immemorial made possible remarkable and significant comparisons of the effects of cultivation for agricultural crops with natural undisturbed conditions on surficial runoff and soil-erosion.

Experimentation in California--These studies were continued as a part of the program of the California Forest Experiment Station by the senior author, assisted by the junior author at the North Fork installations. The studies in California were designed to evaluate the influence of forest-cover on surficial runoff and soil-erosion as it may affect water-supply and utilization in regions of critical water-shortage. The program of experimentation under the project of forest-influences in the California Forest Experiment Station calls for installations in typical regions in California, three of which have thus far been represented. The problem of the rôle of the mantle of natural vegetation, of range-cover, chaparral and high forest-cover on the maximum beneficial yield of water is complex. As has been indicated in former papers by the senior author, factors operating in watersheds are of sufficient complexity and interrelation to prevent the isolation of single factors by stream-flow measurements alone. The evaluation, therefore, of several factors within such a watershed complex requires a series of experimental determinations to measure the comparative effects of each factor.

Such was the object of a series of runoff installations near North Fork, on the Sierra National Forest, in Madera County, California. The plan of this experiment was to measure the influence of unburned forest-cover of the transitional zone in California, as compared with soil-surfaces bared by forest-fires. Comparison of the effect of cultivation was not measured in this experimental installation.

The North Fork experimental area is located within the San Joaquin River drainage of Central California at an elevation of 2560 feet. It lies in the upper region of the foothill belt or woodland brush type of the Sierra Nevadas in the Upper Sonoran lifezone, and in a transitional type between woodland brush type and Ponderosa forests of the higher slopes of the Sierra Mountains. The type represented has particular importance as a watershed cover in relation to reservoir-storage of the California statewide water plan.

In Central California below the 2500-foot contour precipitation occurs almost entirely as rain; between the 2500- and 5000-foot contours it occurs as rain and snow, and above the 5000-foot contour almost entirely as snow. Snow-packs above 5000 feet contribute from 80 to 90 per cent of the water-supply. Drainage-slopes below 5000 feet contribute the principal flood-flows following rain-storms. Watershed areas bared of natural covers of vegetation by fire, destructive lumbering, or heavy grazing are thereby subject to accelerated erosion. It is desirable to have a measure of the effects of destruction of natural vegetation upon accelerated runoff and erosion as they may affect the life of projected water-development on a large scale within this area.

The climate prevailing in the North Fork area is Mediterranean in type (Russell, 1931) and is characterized by winter rainy seasons and long, dry, hot summers. Temperatures vary from January minima of 10° F and maxima of 70° F, and July minima of 60° F and maxima of 105° F.

The soil of the experimental area, selected as typical of the wide area of the Sierra Nevada foothills, is residual, being derived from Grano-diorites, and is characterized by immature profile-development. The soil is designated as a fine sandy loam of the Holland-Sierra series. The slope is broad and approximating a plane, varying in gradient from 30 to 50 per cent. The profile-characteristics of the soil are set forth in Table 1.

Table 1--Profile-characteristics of Sierra soil-series, North Fork Experimental Area

Horizon	Depth	Description
	inches	
A_0	Trace - 0.75	Litter-accumulation, 5-8 years, decompositional contact with soil
A.1	0.1 - 0.5	Dark organic layer, soil fauna active
A.2	9.0 - 12.0	Fine sandy loam, perforated with insect burrows, and dead root-channels; root-zone of living plants; macro-structure, porous
B:	18 - 24	Zone of accumulation moderately developed; roots up to 1.0-inch diameter; decayed roots as conspicuous channels; gopher-burrows; large grub-worm and spider burrows
C:	?	Weathered Grano-diorite in place

Note--Soil was honeycombed by burrows and channels, a conspicuous feature of soil-profiles exposed in periodic soil-moisture sampling to depths of 36 inches.

Since the gold-rush days of the '50s the site had been overrun by frequent forest-fires and unlimited grazing until administered by the United States Forest Service. The vegetative cover had been burned ten or twelve years prior to the initiation of experimentation in 1929. Grazing was excluded by fencing in 1929.

Typical vegetation covering the site consists of scattered digger-pine (Pinus sabiniana), Ponderosa pine (Pinus ponderosa), black oak (Quercus wislizenii), and incense cedar (Libocedrus decurrens), on most northerly slopes, and an understory of chaparral species such as Ceanothus cuneatus intergerrimus, Cercocarpus betuloides, and Rhamnus crocea, var. illicifolia.

Also with these chaparral species were numerous herbs and the following grasses: Bromus rubens, Bromus rigidus, Bromus hordeacaeius, Festuca megalura, and Festuca microstachys.

Accumulation of a ground-litter since the last fire at least ten years prior to the installation had reached varying depths, from a trace to 0.75 inch deep. Generally there had developed a decompositional contact of the litter with the soil. Worm-castings were noticeable on the litter-surface. The essential protection of the pores and channels into the soil had been effected by the layer of litter. The experimental results disclosed the importance of the litter-cover although thin at the surface of undisturbed soil-profiles. The natural vegetation gave a crown-coverage of 0.6 and the litter-coverage of 0.9.

Experimental procedure--The experimental equipment designed and installed for the purpose of evaluating the factors indicated, follows the bordered-plot method which has found favor among experimenters in erosion, and adopted by the senior author in 1924. The plots have areas each of one-fortieth acre, and projectional dimensions of 10 feet by 109 feet. The plots were bordered by planking inset six inches into the soil, and connected by special galvanized iron sleeves. At the lower end of the plots concrete baffle-troughs, which were roofed over to exclude overhead rain, discharged through four-inch pipes into elutriating silt-traps and thence into automatic recording tipping-bucket instruments. The tipping-bucket instruments were connected electrically with a Bristol strip-chart recording device, located in an instrument-house. An automatic tipping-bucket rain-gage was similarly connected to the recorder. By this means intensity of rainfall may be correlated with rate of surficial runoff from each surface-condition represented by the runoff-plots.

Eroded material was caught in the large baffle-trough and in silt-traps. The major bulk of material lodged in the baffle-trough; and the silt-trap served to remove by elutriation all material in suspension in excess of the clay-fraction.

The plots were protected from ingress of runoff from outside the area by a double series of ditches above and along the sides of plots. No instance of invasion, or escape of runoff except as experimentally provided for, occurred throughout the period of experimentation reported.

The steps in experimentation were as follows: Natural vegetation on the experiment was first mapped. Two plots, 10 feet by 109 feet, for duplicating conditions under the unburned natural cover were established and designated 401 and 402 (Fig. 1). Similar areas of the broad slope were cut clean, and the brush- and tree-growth was spread evenly over the ground and burned, when dry, to produce the effects of a hot forest-fire. One pair of plots, designated 403 and 404 (Fig. 2), was located on a surface burned in 1929. The third pair of plots, numbered 405 and 406 (Fig. 3), was located on a portion of the slope burned clean in 1930.

The plan of experimentation comprised the following procedure: One pair of experimental plots was to be run throughout the life of the experiment with the natural cover unburned and undisturbed. One pair of plots was located in a burned area and the vegetation burned clean at the end of each dry season after the second year, thus maintaining the plot in as barren a condition as possible throughout the life of the experiment. The third pair of plots was located in an area burned clean in 1930 but thereafter the vegetation was permitted to return naturally without disturbance, as shown in Figure 3. This procedure was considered advisable in view of the wide variation of intensity of storms from year to year. Thus one pair of plots would be maintained in a barren condition to record the effects of unusually intense storms whenever they might occur, such as fell in the rainy season of 1933-34. The installation is maintained for experimental purposes to represent a wide range of rainfall-conditions for a number of years.

Experimental results--The experimental results here reported cover a period of from 1929 to 1934 only in summary. The full report of this experiment is to be made at a later time in a bulletin wherein detailed results by individual storms will be set forth for the entire period. For the purpose of this report there have been selected six major storms which fell during the experimental period. These storms represent the more extreme results such as have particular interest to hydrologists

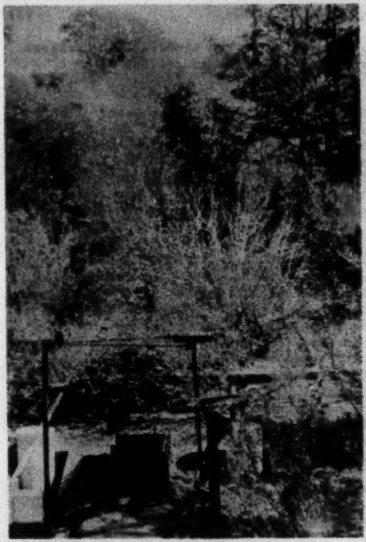

Fig. 1

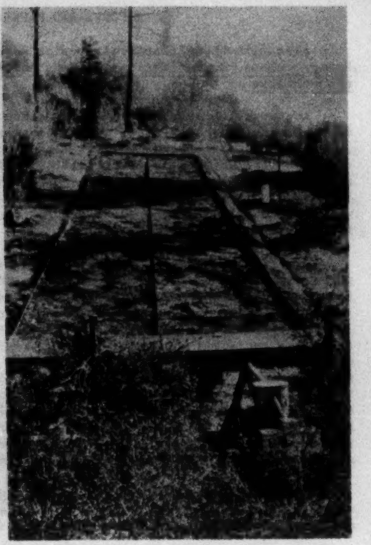

Fig. 2

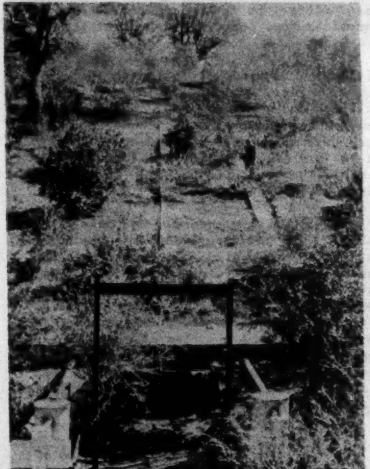

Fig. 3

NORTH FORK RUNOFF- AND EROSION-PLOTS

Fig. 1--Undisturbed cover of natural brush, Sierra brush-type, Sierra National Forest Plots 401 and 402

Fig. 2--Plots burned in 1929, 1931, 1932, and 1933, Sierra brush-type, Sierra National Forest Plots 403 and 404

Fig. 3--Plots burned in 1930 and regrown three years, Sierra brush-type, Sierra National Forest Plots 405 and 406

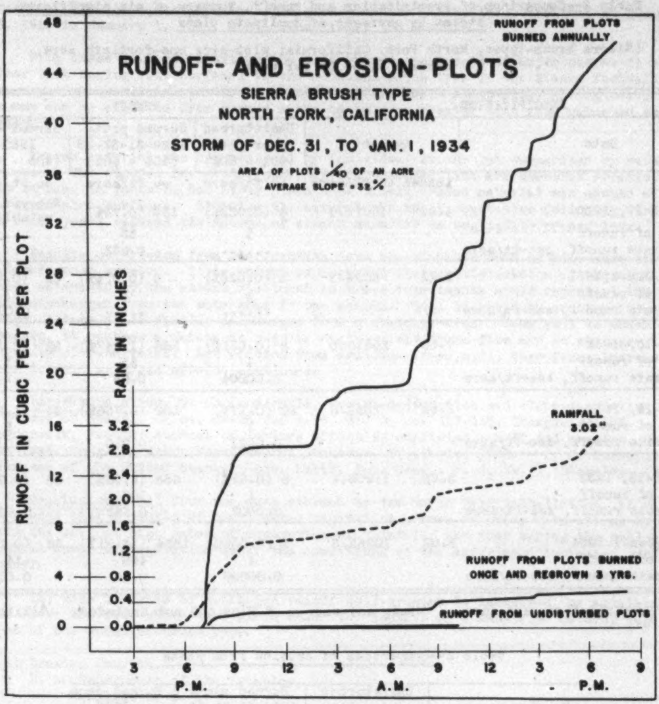

Fig. 4

and water-supply and flood-control engineers in the design of structures. The results are set forth in Tables 2 and 3.

Discussion of results--Comparisons of the runoff and erosion from the averages of the paired plots are significant. During the rainy season of 1929-30, two pairs of plots (401, 402, and 403, 404) were installed. Plots 403 and 404 were located within a freshly burned area. For the major storm of this season, surficial runoff from the bared plots was 33 times that from the plots in unburned natural cover.

In 1930 a third pair of plots (405 and 406) was installed within a freshly burned area. The plots 403 and 404 were not reburned this year. It is interesting to note that the rate of runoff from the second pair of plots dropped down in relation to unburned plots, whereas the freshly burned new plots showed a runoff-ratio of 31 to 1, much like the freshly burned plots of the former year.

From the year 1930, the working plan called for annual re-burns on plots 403 and 404, while plots 405 and 406 were left untreated to permit native vegetation to return naturally. From this time on it will be seen that whereas the ratio of runoff is greater than that from unburned surfaces, yet the magnitude is small. The effects of surficial runoff from freshly burned plots are shown to reach high values for major

Table 2--Comparison of precipitation and runoff, summary of six significant storms by averages of duplicate plots

(Sierra brush-types, North Fork, California; plot-area one-fortieth acre, average slope 32 per cent)

PRECIPITATION			RUNOFF		
Date	Amount		Undisturbed cover-plots (401 - 402)	Burned plots 1929-31-32-33 (403 - 404)	Burned once 1930 (405 - 406)
	inches	cu ft/acre	cu ft/acre	cu ft/acre	cu ft/acre
Feb. 19-27, 1930	4.98[a]	18077.4	4 (0.022%)	132 (0.73%)	Not yet established
Ratio of runoff			1	33	..
Max. rate runoff, sec-ft/acre			......	0.083	......
Dec.31-Jan.2,1931	2.23	8094.9	2 (0.025%)	6 (0.074%)	62 (0.766%)
Ratio of runoff			1	3	31
Max. rate runoff, sec-ft/acre			......	.....	0.010
Feb. 4-10, 1932	7.00[b]	25410.0	8 (0.031%)	266 (1.047%)	92[c] (0.362%)
Ratio of runoff			1	33	11
Max. rate runoff, sec-ft/acre			0.00004	0.05	.....
May 10-12, 1933	2.02[d]	7332.6	20 (0.27%)	202 (2.755%)	94 (1.282%)
Ratio of runoff			1	10	5
Max. rate runoff, sec-ft/acre			0.0021	0.020	0.01
Dec. 12-15, 1933	3.28	11906.4	6 (0.05%)	638 (5.36%)	88 (0.74%)
Ratio of runoff			1	106	15
Max. rate runoff, sec-ft/acre			0.0002	0.382	0.035
Dec.31-Jan.1,1934	3.02	10962.6	4 (0.036%)	1854 (16.91%)	56 (0.51%)
Ratio of runoff			1	463	14
Max. rate runoff, sec-ft/acre			0.00005	0.56	0.01

[a] Precipitation part snow. [b] Rain and snow. [c] Plot 406 not included. [d] Rain and snow.

Table 3--Comparison of erosion from plots

Erosion-season	Undisturbed cover-plots (401 - 402)	Burned plots 1929-31-32-33 (403 - 404)	Burned once 1930 (405 - 406)
1929-30			
Cu ft/acre	0.28*	66.8	.....
Ratio of erosion	1	239	..
1930-31			
Cu ft/acre	0.13	6.24	63.08
Ratio of erosion	1	48	485
1931-32			
Cu ft/acre	0.1	2.2	8.12
Ratio of erosion	1	22	81
1932-33			
Cu ft/acre	0	1.92	0.17
Ratio of erosion	..	..	..
1933-34			
Cu ft/acre	0	100.0	0.1
Ratio of erosion	..	..	..

*Largely organic material.

storms. Thus the ratios for the storms of December 12-15, 1933, and that of December 31, 1933 to January 1, 1934, were respectively 106 and 463.

From these data representing the more extreme responses of major storms it seems clear that baring soil-surfaces in the woodland-brush type of the Sierra foothill-belt increased the surficial runoff to significant degrees. Flood-flows during heavy storms can be expected from burned areas to be much greater than from unburned surfaces.

Eroded material was not measured by individual storms but summarized by rainy seasons. The figures for eroded material are seasonal, and are somewhat erratic, as may be seen in Table 3, but it is plain that little eroded material was washed off the unburned-plot surfaces. Likewise the natural return of vegetation following fires had in three years reduced the amount of eroded material to negligible proportions.

Results on erosion from one-fortieth acre runoff-plots such as these must be considered gross erosion. It is not to be expected that multiplication of the area of a large watershed by the amount disclosed in these experiments would represent the erosion discharged from the watershed in one season. Soil is moved by erosion in many stages before it is finally discharged from a drainage-area. Once soil is under way, however, it becomes a menace to regular regimens of stream-flow and to storage-capacity of reservoirs. Net erosion from drainage-areas will, therefore, increase from year to year as gross erosion continues.

Literature cited--W. C. Lowdermilk, Forest-destruction and slope-denudation in the Province of Shansi, China, China J., v. 4, No. 3, pp. 127-135, Shanghai, 1926. W. C. Lowdermilk, Further studies of factors affecting surficial runoff and erosion, Proc. Internat. Cong. Forestry Experimental Stations, Stockholm, 1929. R. J. Russell, Dry climates of the United States, Univ. Calif. Pub. Geog., v. 5, No. 1, Berkeley, 1931.

Conclusions--(1) From the data yielded by the North Fork installation, it may be concluded that a mantle of undisturbed vegetation serves in heavy rain-storms to maintain the soil at high rates of absorption of rainfall, and that baring the soil of its natural cover of vegetation under the conditions of the experiment increases surficial runoff.

(2) With increase of surficial runoff soil-erosion is increased, or accelerated far above the rate which took place under the control of a mantle of natural vegetation of the woodland-brush type.

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A QUANTITATIVE STUDY OF CERTAIN FACTORS AFFECTING SOIL- AND WATER-LOSSES AS THE LOGICAL BASIS FOR DEVELOPING PRACTICAL METHODS OF EROSION CONTROL

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Efforts at a quantitative study of the physical factors affecting the rate and amount of erosion and surface-runoff show that a wide range of natural forces, many of them uncontrollable, affect the results. Among the latter type are to be included those of a climatic nature such as intensity, duration and frequency of rains, as well as the time of their occurrence, especially with reference to particular surface-conditions such as frozen, dry, or saturated soils, etc. Those factors having to do with topography also are included in this group, since the degree of slope is doubtless one of the most important influences controlling the course of erosion.

As opposed to these uncontrollable factors a large number of others also are under study which are quite amenable to practical control but which, at the same time, have marked effect on erosion and runoff. For instance, the type of vegetative cover, as well as the timeliness of seeding and development of same with reference to the normal rainy season, are matters of extreme importance. Likewise the type of cultivation, its frequency, the size of fields as they affect length of slope, direction of cultivated crop-rows, applications of mulch, time and method of plowing, and many other factors are known to exert direct effect on the rate and amount of soil- and water-losses.

Thus the correct design of erosion control-measures is importantly dependent on specific information centering around three groups of factors: (A) Those affecting the infiltration-capacity of the soil; (B) those affecting the capacity of the surface-storage reservoir; and (C) those affecting the density of the runoff-material. Practical control measures are primarily included in one or more of the above groups. Increase of infiltration-capacity or of the storage-capacity of the surface, or a reduction of the density of the runoff-material, either alone or in combination has a pronounced effect on the degree of erosion. Some data of interest bearing on these items have been obtained at the Soil Erosion Experiment Station of the Missouri Valley Loess Region located in southwestern Iowa.

The data presented in this paper are from experiments on Marshall silt-loam, an extensive soil typical of the Missouri Valley Loess. In many respects the results doubtless may be regarded as essentially similar to those which would be obtained from other loessial soils, particularly those having considerable depth. The Marshall silt-loam is a fairly porous, open-structured soil, containing 59.0 per cent of silt, 32.4 per cent of colloid, and having a dispersion ratio of 16:1. Physical and chemical studies on this soil have been made in considerable detail (H. E. Middleton, C. S. Slater, and H. G. Byers, Physical and chemical characteristics of the soils from the erosion experiment stations, U. S. Dep. Agric. Tech. Bull. 316, 1932). The infiltration-capacity, per se, naturally is closely related to the depth and physical properties of its profile. Since loessial soils usually are comparatively porous and deep, they commonly present much higher infiltration-capacities than those of most other soils of greater density.

Infiltration-capacity

The infiltration-capacity of Marshall silt-loam has been studied for normal soil in the field under numerous conditions. First, it has been determined for a three-foot column of soil of undisturbed structure in a set of erosion-type lysimeters, in which surface-runoff is freely permitted and the percolation through the three-foot column is caught and measured. [A description of these lysimeters is now in manuscript for early publication.] This capacity also has been determined in the field by the use of methods which give indicated results for soil of full field-depth.

These rates have been calculated after the manner of Horton (R. E. Horton, Trans. Amer. Geophys. Union, fourteenth annual meeting, 1933, p. 446). Individual records from the Fergusson gage showing intensity of rain were used and the measured runoff deducted from the portion of the intensity-curve covering the runoff-period. The remainder indicated as the amount of rainfall absorbed is then converted to inches per hour. Only those rainfall-records were used for the data of Table 1 which were associated with runoff. For rainfall not producing runoff somewhat higher infiltration-rates were indicated, but these rains averaged a much shorter duration and as such are not suitable for general use in the design of control-measures.

The results of the direct measurement in the erosion-type lysimeters center largely around the figure of 0.74 inch of water absorbed per hour. For short periods of time higher rates are occasionally obtained, but this figure repeatedly occurs and so frequently that it is regarded as a fairly safe approximation of the rate of water-absorption for a three-foot column of Marshall silt-loam. This rate of infiltration also applies directly to areas which are planted to corn on a slope of 8 1/2 per cent.

The indicated infiltration-rates from field-conditions of various kinds as an average for the years 1932 and 1933 including all records are given in Table 1. The data of Table 1 have been obtained from the same soil-type having the same slope as that of the lysimeters. It is of extreme interest to note that the indicated infiltration-rates for the corn-plots on normal soil (0.76, 0.72, and 0.71 inch per hour) approximate so closely the data obtained from the lysimeters by direct measurement (0.74 inch per hour). The indicated infiltration-rate for alfalfa (0.79 inch per hour) is probably somewhat lower than more complete figures would give, inasmuch as the period covered by the data includes in the first portion of 1932 a rather long period during which the vegetative cover was becoming established. The same is also true of the blue-grass treatment. The data for these two treatments during 1933 give indicated infiltration-rates of 1.04 and 1.00 inches per hour, respectively. For corn grown on the desurfaced soil (which contains 3 1/2 per cent less silt and 3 per cent more clay as well as 2.2 per cent more colloid than the normal soil), a somewhat lower infiltration-rate is found, as would be expected.

Table 1--Indicated absorption-rates for field-conditions, 1932 and 1933

Treatments	Length of slope	Average duration	Indicated absorption-rates
	feet	minutes	inch/hr
Corn..................................	36.3	48	0.75
Corn..................................	72.6	48	0.72
Corn..................................	145.2	51	0.71
Alfalfa...............................	72.6	46	0.79
Blue-grass............................	72.6	39	0.91
Corn (surface-soil removed) on subsoil	72.6	46	0.67

To a considerable degree the infiltration-capacity of this soil is an inherent quality which is probably more largely affected by the genesis of the soil than by subsequent treatment. The fact that subsequent treatment may affect the infiltration-capacity, however, is indisputable and has been indicated in a number of experiments other than those shown in the above Table.

Table 2--Effect of additions of organic matter upon volume of runoff

Series	Period	Treatment	Total precip.	Runoff	Comparison and calculated odds*
			inches	surface-inches	
Fallow	Aug. 31, 1932 to Dec. 31, 1933	Check	34.06	7.32	
		8 tons/acre manure		5.03	(Versus check) 140:1
		16 tons/acre manure		3.71	(Versus check) 203:1
Corn	Aug. 1, 1932 to Dec. 31, 1933	Check	39.87	5.87	
		8 tons/acre manure		3.37	(Versus check) 6999:1
		16 tons/acre manure		1.96	(Versus check) 9999:1

*Determined by Students Method of Pairs; the usually accepted odds of 30:1 are used as a test for significance; this method of calculation is used throughout.

The effect of additions of organic matter, in the form of well-rotted stable manure incorporated within the surface six inches of soil on the volume of surface-runoff, is an indirect index of the effect of these treatments on infiltration. In the fallow-series the first increment of treatment effected a reduction in runoff of 31 per cent and the second extended the reduction in runoff to 49 per cent. In the corn-series, however, the first increment effected a reduction in runoff of 43 per cent while the second extended the reduction in runoff to 67 per cent. This more pronounced control obtained under the corn-series unquestionably is due to the dual effect of the organic matter on the crop as well as on the soil. This is evidenced by the very marked increase in yield resulting from these treatments. Obviously the infiltration-capacity of the soil has been very appreciably increased by the applications of organic matter both to the fallow-series and to the corn-series, it having also greatly stimulated plant-growth upon the latter.

The effect of additions of organic matter upon the infiltration-rate is also found by direct measurement in the lysimeter-series. Treatments made in triplicate were identical with those made in the field, as given in Table 2 above. That is, applications of 16 tons per acre of manure were incorporated in the surface six inches of soil on each of three lysimeters, and these were compared with three others without such organic-matter additions. Corn was grown upon all of them. The results for the period are given in Table 3. In these treatments as in the field-treatments given in Table 2, the runoff has been appreciably reduced, likewise the density of runoff, and also the total erosion. The effect of the additions of organic matter upon the infiltration is shown directly by the percolation through the three-foot column of soil totaling approximately 100 per cent more where the organic matter has been incorporated.

The effect of the treatment upon the density of runoff is in full conformance with other data, examples of which are cited in Tables 5 and 6 hereinafter.

The Marshall silt-loam then, with an average infiltration-capacity of approximately

Table 3--Effect of additions of organic matter as determined from triplicate treatments on lysimeters, May 5 to Dec. 31, 1933 (total precipitation 23.52 inches)

Item	Corn	Ratio corn to organic matter	Odds
Erosion in tons per acre	19.70	4.43	104:1
Runoff in surface-inches	4.13	2.35	533:1
Density of runoff in pounds per cu ft	2.62	1.04	39:1
Percolation in surface-inches	0.76	1.51	

3/4 inch of rainfall per hour, would appear to be a soil which is markedly susceptible to artificial treatment for the control of erosion and the conservation of moisture. Knowing that the soil has an infiltration-capacity of this amount, it is only necessary to design treatments having a known effect on the capacity of the surface-storage reservoir to obtain control-measures which are protective to a definite and predetermined degree. For instance, given an infiltration-rate of 3/4 inch an hour and a capacity of the surface-reservoir of 1 1/2 surface-inches (which may be obtained, for example, with the contouring of crop-rows), it is seen that the combined effect should provide a total protection of at least 2 1/4 inches of rain in the first hour, 3 inches in two hours, 3 3/4 inches in three hours, 4 1/2 inches in four hours, etc.

Table 4--Comparative capacities for control of runoff on two soil-types of different infiltration-rates (both areas contoured to retain 1.5 surface-inches upon the field)

Period	Pervious soil, infiltration-rate 0.75 inch per hour		Pervious soil, infiltration-rate 0.75 inch per hour		Maximum observed rainfall[a]		
	Capacities for period	Equivalent	Capacities for period	Equivalent	Des Moines	Omaha	Kansas City
Minutes	inch	inch/hr	inch	inch/hr			
5	1.56	18.75	1.51	18.10	0.66	0.67	0.57
10	1.63	9.75	1.52	9.10			
15	1.69	6.75	1.52	6.10	1.36	1.27	1.15
30	1.87	3.75	1.55	3.10			
45	2.06	2.75	1.57[b]	2.10			
60	2.25	2.25	1.60[b]	1.60	2.65	2.53	4.74
120	3.00	1.50	1.70[b]	0.85			
180	3.75	1.25	1.80[b]	0.60			
240	4.50	1.12	1.90[b]	0.47			

[a] From Jarvis, Rainfall characteristics, Trans. Amer. Soc. C. E., v. 95, p. 410, 1931; years of record Des Moines 42, Omaha 57, Kansas City 33; no data on expectancy.

[b] Indicates probably insufficient protection.

Capacity of surface-storage reservoir

The relation of the surface-configuration of a field to its capacity for storing precipitation or for retarding the movement of such water down the slope may be very materially affected by a number of treatments. Among these are the following: (A) The contouring and ridging of row-spaced crops; (B) listing and constructing small soil-dams; (C) terracing; (D) the use of the hole-digging cultivator; and (E) the type of tillage-operations practiced, for example, "rough" plowing, "balk" plowing, etc.

One of the most practicable of these treatments on permeable soils of the corn-belt where storage-capacities within a range of two surface-inches only are required, is that of contouring and ridging of row-spaced crops. In the corn-belt normal cultivation-practice would provide a surface-storage capacity of 1 1/2 inches if the contouring of rows were practiced. This amount of storage is of course impracticable to obtain except on very uniform slopes. Excessive ridging, however, is not necessary to secure a capacity of this degree. Where listing is practiced much greater capacities may be developed.

Treatments of this character have been established and comparative, quantitative measurements made. Corn, contoured in one case, and in the other grown in rows running up and down the slope, was planted under otherwise similar conditions. The degree of slope (8 1/2 per cent) is representative of much of the rolling Missouri Valley lands.

A detailed survey of surface-elevations was made and the theoretical degree of protection calculated on the basis of an infiltration-rate of 3/4 inch per hour and a surface-storage capacity of 1 1/2 inches. Results for the year 1933 are given in Table 5.

Table 5--Effect of row-direction on capacity of the surface-storage reservoir and upon erosion and runoff for Marshall silt-loam (slope 8.4 per cent, precipitation 26.37 inches)

Item	Corn	
	Rows in direction of slope	Contoured rows
Length of slope	157.5'	157.5'
Capacity of storage-reservoir in surface-inches	.....*	1.5
Erosion in tons per acre, 1933	11.20	...
Runoff in surface-inches, 1933	3.06	...
Ratio of soil to runoff in pounds per cu ft	2.02	...
Seasonal average per cent soil-moisture		
Top of slope	24.66	27.44
Middle of slope	24.54	28.06
Bottom of slope	23.60	26.79
Corn-yield in bushels per acre	32.93	55.97

*Ridged to same degree as comparative treatment but row-direction provides in effect open-ended shallow trenches permitting free flow down the slope; the length of slope itself is the only factor tending to retard such movement.

The significance of these moisture-determinations has been tested by Students Method of Pairs, resulting in calculated odds in excess of 9999:1 against the occurrence of such differences being due to chance alone. In the case of the erosion and runoff, of course the odds are infinite.

During the period of operation of this Erosion Experiment Station no rains occurred which, in intensity and duration, approach the theoretical capacity of the treatment (4 1/2 inches in 4 hours) for control. However, on August 21 a rain occurred of magnitude rare in the history of the local Weather Bureau. This rain followed upon a series of small, slow rains, the last of which on the day preceding the record brought the soil-moisture content to practically the saturation-point. There then followed a total precipitation of 3.31 inches in 4.66 hours. Neither runoff nor erosion resulted from the contoured treatment, showing that practically the infiltration-capacity and storage-reservoir were of such size as to fully take care of this amount and intensity of rain.

The same treatment, but without measuring device, has been under observation at the Experiment Station for a period of three years, during which time the results have been in full conformity with those cited above.

Density of surface-runoff

Like volumes of runoff from different agricultural areas may provide notably different degrees of erosion. A great many treatments have remarkably different effects upon the mass of soil moved per unit volume of runoff-water. Under many types of rain the runoff from sodded areas may be relatively large, yet because of the treatment the water is practically clear, and little erosion results. As an example of this effect, two areas may be taken which have the same soil, same degree of slope, same length of slope, and are in all other respects similar, excepting that one of these was in corn continuously and the other in alfalfa. The results of this comparison are given in Table 6. From Table 6 it is seen that, while the effect of the alfalfa reduced the volume of runoff to approximately one-half, the erosion was reduced to less than 1/40 of the amount yielded by the area in corn. The effect of the treatment is thus such as to greatly reduce the density of the runoff-material. The comparatively high calculated odds show that this effect has been very consistent throughout the entire period, and is more significant for density of runoff than for either erosion or volume of runoff.

A study of the rather large mass of data now available shows that this effect on density of runoff is frequently more significant from the statistical viewpoint than is that on erosion and surface-runoff. As an example, comparison may be made between two

Table 6--Effect of corn and sod upon the density of runoff-material and upon erosion and runoff

Period	Item	Continuous corn	Alfalfa	Calculated odds
June 1, 1932, to Dec. 31, 1933 (precipitation 47.45 inches)	Erosion in tons per acre	44.68	1.19	130:1
	Runoff in surface-inches	5.99	3.11	105:1
	Density of runoff in pounds per cu ft[a]	4.11	0.24	225:1

[a] For each runoff-record the total quantity of dry soil and of soil-free water are separately determined. The ratio of dry soil to clear water is here expressed as pounds of soil per cubic foot of runoff-water.

areas in corn continuously, one of which is on normal soil, and the other on desurfaced or artificially eroded soil. It has been shown above (in Table 1) that the normal soil has a somewhat higher infiltration-capacity than the artificially eroded soil. However, the latter soil has a higher infiltration-capacity for short periods of time; that is to say, for rains which do not saturate the soil, full absorption commonly occurs on this desurfaced soil, whereas the normal soil may not fully absorb the precipitation. The results from these two areas are given in Table 7.

Table 7--Effect of normal and artificially eroded soil upon density of runoff-material and upon erosion and runoff

Period	Item	Continuous corn		Calculated odds
		Normal soil	Artificially eroded soil	
June 1, 1932, to Dec. 31, 1933 (precipitation 47.45 inches)	Erosion in tons per acre	44.68	81.03	12:1
	Runoff in surface-inches	5.99	7.35	3:1
	Density of runoff in pounds per cu ft	4.11	6.08	93:1

The total erosion from the artificially eroded area is thus nearly twice as great as that from the normal soil. The calculated odds show, however, that this effect is not consistent. In fact, in many of the individual records it is found that the erosion resulting from rains of certain character has been greater on the normal soil than on the artificially eroded soil. In the case of surface-runoff it is also seen that the total is greater on the artificially eroded plot, yet the odds of 3:1 indicate that this effect likewise is not consistent. However, in the case of the ratio of soil to runoff it is found that the artificially eroded area quite consistently carries a larger mass of soil per unit volume of water than does the runoff from the normal soil. Similar effects have been found in other treatments, such, for example, as the application of organic matter, the rotation of crops, the effect of length of slope, and others.

Discussion

In designing experiments for the control of erosion it has been impossible in many instances in the past to plan such work on the basis of specific information. There is at the present time a dearth of information particularly in relation to the infiltration-rates of various field-soils. Such information to be usable must be derived from soils of normal structure and laboratory determinations are largely impracticable. Particularly for those soils which absorb precipitation to an appreciable degree it is extremely important to know the rate at which such absorption occurs. Such information is required for the soils of any region in which control-measures are being planned, as well as for the various conditions of treatment which affect the rate of absorption of such soils.

As pointed out above, the inherent physical properties of the soil more largely affect the infiltration-rate than do any of the subsequent treatments which may be applied. It is of extreme interest to know that practical treatments may appreciably affect the infiltration-rate to any degree at all. For the Marshall silt-loam and the soils of the Missouri Valley Loess region much additional information is needed other than that which has been cited above. The results which have been cited indicate the trends which may be expected for various treatments and various conditions. It is planned during the current year to systematically and intensively study the effect of such variable conditions and treatments of this soil upon absorption-rates. For this work a new technique for making rapid direct measurements in the field is now under test, and very promising results are being secured.

The mere fact, however, that the magnitude of normal infiltration is known provides a basis for planned control-measures including increased surface-storage capacities, which measures are then effective in reducing the volume of runoff to a definitely predetermined degree.

The capacity of the surface-storage reservoir upon a given field is susceptible of considerable modification through slight changes in normal farm-practices. Where a storage-reservoir of suitable capacity can be provided by such means, the cost is usually relatively low. The necessary equipment under such conditions is ordinarily available upon the farm and the amount of labor is usually little if any greater than normal.

The reduced density of the runoff is one of the most important results following the application of field-treatments in many areas. It is often more significant from the statistical standpoint than any of the other effects of the treatments. Where the density of the runoff is reduced at the same time the volume of the runoff is reduced, the final effect upon total erosion is then extremely marked. Such results have been demonstrated and fully established by means of numerous treatments upon many soil-types. In this work it is invariably shown that close-spaced crops and particularly sod-formers exert pronounced effects of this kind.

From this discussion it may be indicated that in general the methods of control which may be recommended for impervious soils are quite different from those which may be recommended for pervious soils, or those of high infiltration-rates. Only on the latter can the increased capacity of the surface-reservoir obtained through modifications of farm-practice be depended upon to supply a sufficient degree of control. On the impervious soils it is necessary to depend largely upon factors affecting the capacity of the reservoir, and the density of the runoff. For these soils the latter particularly includes the more potent group of factors. A consideration of these points brings out a fact which is otherwise well recognized, namely, that control-measures are necessarily more difficult to obtain as well as more expensive to establish upon the impervious soil-types.

Conclusions

To summarize, the primary factors determining the design of control-measures are those affecting: (A) The infiltration-capacity of the soil; (B) the capacity of the surface-storage reservoir; and (C) the group of factors affecting the density of the runoff-material.

While the infiltration-capacity is largely determined by the inherent qualities of the soil, definite improvement may be effected, for example, by incorporation of organic matter, by attention to the character and condition of the vegetative cover, etc.

The capacity of the surface-storage reservoir may be modified within limits by tillage-practices and by terracing.

An extremely potent factor affecting the density of runoff is the type of vegetative cover. The density of runoff in turn is a most potent factor in determining the total amount of erosion.

All of these factors may be quantitatively determined and, from such information, the basis laid for a sound system of erosion-control under field-conditions.

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PAPERS

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UNDERGROUND STORAGE BY SPREADING WATER

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(Abstract)

The first recorded attempt at conservation of water by spreading is that of the Denver Union Water Company in 1889. In California water has successfully been spread since 1896 on the Santiago Creek detrital cone and since 1900 on the Santa Ana River cone. Both of these projects have been much improved and enlarged since that time until they now assume a place of major importance in the conservation of water in these areas. For a number of years water has also been spread on San Antonio and Lytle creeks and for shorter periods in Arroyo Seco, San Dimas, Piru, Waterman, City, and Mill creeks, and on San Gabriel, San Jacinto, San Gorgonio, Whitewater, and Santa Clara rivers.

The most important factor to be considered in selecting spreading-grounds is the geological formation. Favorable topography or an abundant water-supply for spreading may be entirely worthless unless suitable geological conditions prevail. Spreading-grounds are located on alluvial fans and detrital cones built up by masses of clay, sand, gravel, and boulders brought down from mountains by successive floods. We must remember, however, that the resulting formations are classified in three groups, namely, the non-absorptive, semi-absorptive, and absorptive. It is with the latter we are concerned in water-spreading.

In selecting suitable spreading-grounds, we must also consider topographic conditions, such as slope, area, location with respect to diversions, surface and underground drainage, direction and rate of underground movement of water, etc.

There are four general methods of spreading water for storage, namely, lateral spreading in a pool above a detention dam, running water in porous ditches and thence to absorptive areas of either natural or specially prepared ground, running water to areas forming a series of basins, and delivering directly to the underground storage by means of wells or of shafts and tunnels. Each of these has its merits and specific conditions govern their use.

Possibly the three outstanding cases of different types of layouts for spreading on a large scale are the spreading-systems on Cucamonga cone, Lytle Creek cone, and the Upper Santa Ana cone, all in San Bernardino County, California. On the Cucamonga cone, the layout consists generally of a series of detention-dams forming settlement-basins followed by diversion-works and many miles of ditch-systems designed to "wear the water out." The Lytle Creek layout has no dam or basin-system but takes the water directly from the flood-stream and diverts it through many miles of ditches. It also employs the well-and-shaft method of sinkage. The Upper Santa Ana River system takes its water from a diversion-dam and diverts it through a ditch-system to its spreading-area.

For the past six years the Division of Irrigation of the Bureau of Agricultural Engineering has been conducting research studies of factors considered influential in efficient water-spreading with particular emphasis on rate of percolation through the different prevailing soil-types and formations, efficiency of the different methods of spreading on some soil-types, effect of temperature on rate of percolation, effect of rise and fall of ground-water table on rate of percolation, the effect of spreading silty water on the efficiency of the spreading-area, and other incidental factors. The results of these studies are being prepared for publication. Data developed by some of these studies show that on the same soil-types under the same conditions spreading-areas in natural state, that is, with the vegetation undisturbed, percolated 1.7 times more water than the furrowed plot and 1.3 times more than a basined plot, for an average of 155 days.

We found that temperature has some effect upon percolation-rates, but the change in the temperature of either the air, soil, or water is usually so small during the spreading-period as to be overshadowed by other more important factors affecting the percolation-rate, and, furthermore, it is merely an incidental factor in spreading flood-waters.

Water-spreading in its true sense has been utilized on a relatively limited area, but should be extended to areas where we know it would be beneficial.

We have many records of areas where the draft on the underground water-supply for agricultural or domestic use or both has lowered the water-table to such an extent as to raise a question as to the economic limits to which the particular use would warrant going in raising water to the surface. Worse still, the future dependability of the supply at any cost may become questionable. We also have records to show that in most cases these lowering water-tables cannot be brought back to an economical status without artificial means.

Division of Irrigation,
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SURFACE SPREADING-OPERATIONS BY THE BASIN-METHOD AND TESTS ON UNDERGROUND SPREADING BY MEANS OF WELLS

D. A. Lane

In the densely inhabitated areas surrounding Los Angeles, due to the scarcity of surface storage-sites, it is essential that all available ground-water storage-basins be utilized.

In the foothill areas several ideal ground-water storage-basins exist, such as the San Gabriel and San Fernando valleys. Each of these basins consists of a coarse granitic material entirely surrounded by mountain ranges with a single confined exit through which all water from the drainage-area must pass either on the surface or underground. While clay deposits exist in these alluvial fills, they are not continuous and are of small consequence, allowing a direct percolation from the ground-surface to the water-table.

The two general types of spreading as practiced are surface and underground. The surface-type may be used in those basins where the water percolates freely from the surface downward to the water-table. This type is divided into the basin- and ditch-methods. The underground type is by means of the sinking of shafts and wells, and due to its greater cost is utilized only in those areas where the presence of continuous clay blankets or layers prohibit a direct contact between the surface and the various water-bearing strata.

The value of the San Fernando Valley as a ground-water storage-basin was recognized many years ago by William Mulholland, then Chief Engineer of the Los Angeles Bureau of Water Works and Supply. He clearly saw that the ultimate control of the Owens River supply would necessitate the use of this ground-water basin as a storage-regulator.

After a survey of all types of spreading-operations in Southern California and actual operation of a test-area for three years, the basin-method was selected as the most suitable for the spreading of Owens River Aqueduct water in the San Fernando Valley.

The net area of the constructed works is 47 acres. The maximum capacity is limited by the Venturi meter to 108 second-feet. Plans for the future development call for a capacity of 200 second-feet.

The spreading-basins average 100 by 400 feet with a depth of three feet. Each basin is fed by a six-inch pipe-line laid in the center and controlled by a valve at the distribution-main. The depth of water is maintained sufficient to cover the bottom of the basin at an average depth of 0.50 foot. The amount of water entering the spreading-area is recorded by a Venturi tube. Each basin is equipped with a staff-gage.

The operating crew consists of four men, three regular operators and a relief man, dividing the day into three shifts of eight hours each. The operating schedule calls for the hourly reading and recording of pressure on both the trunk supply-line and the spreading-area distribution-line, the elevation of each basin staff-gage, and the approximate water-surface area of the basin if not completely covered.

In the center of the spreading-area a meteorological station is set up, consisting of a rain-gage, an evaporation-pan, an anemometer, and a recording air-thermometer. During the operating periods a fluid temperature-recorder is installed in one of the basins. A daily log-book is maintained throughout the year giving all pertinent information.

From tests conducted on the experimental plots, it was believed it would be necessary to remove the silt-crust from the basins. After considerable experimenting on the operating basins, it was found that the use of a spring-tooth harrow, with the teeth set at a depth sufficient to form ridges, broke up the crusts and made removal unnecessary.

Under normal conditions the basins may be operated for periods of from ten to fifteen days between cultivations and the percolation-rate maintained at nearly the maximum rate. Normal winter practice is to allow the basin to dry about three days before cultivation. This is gradually reduced during the spring until warm-weather operation permits a total "off" period of 24 hours or less per basin. The cultivator is operated by a light tractor and the actual time of cultivation is approximately 15 minutes per basin.

During the past three years a total of 68,607 acre-feet has been spread at a seasonal average rate of 6.19 acre-feet per acre per day.

Underground spreading by means of wells--Underground spreading in any great quantity up to the present time has been by means of pits or shafts. There are many areas throughout California that could be materially benefited by spreading, but have not been developed due to the prohibitive cost of the necessary works.

Where the continuous clay-blanket overlies a gravel-deposit and the water-table is below the clay, spreading may be accomplished by pits penetrating through the clay. In those ground-water basins composed of thin gravel-deposits lying between clay strata 100 feet or more in thickness, the cost of pits is so great as to be prohibitive.

In the eastern central portion of the San Fernando Valley, the Los Angeles Bureau of Water Works and Supply has a group of wells known as the North Hollywood or Lankershim wells. They are all 20 inches in diameter penetrating the granitic alluvium deposit to an average depth of about 400 feet. Their pumping capacity is from five to six second-feet per well.

During the winter of 1927 it was deemed advisable to increase the San Fernando Valley underground water through these wells. The results were far from satisfactory. For a few days the wells took considerable water, but soon it was necessary to rapidly decrease the amount of water turned in until after the period of a week or so the amount of percolation was so small as to not warrant the further continuation of this method. Before putting the wells back in operation it was necessary to redevelop in much the same manner as that of bringing in a new well.

It was impossible to measure either the individual or the group of wells, as the water was released from the distribution-main back through the pumps.

The sealing-off effect is quite easily understood if one visualizes that in the pumping of a well all material loosened up in the vicinity of the perforations drops into the casing and is either removed by the pump or settles to the bottom of the well. When the flow is reversed there is a serious disturbance of all materials adjacent to the perforations. The reversed flow moves these particles in towards the soil-body, gradually sealing off a part of the interstices and reducing the amount of percolation.

During the past three years experiments have been conducted with spreading by means of wells located in the Los Angeles Coastal Plain. At the Slauson and Compton Avenue Plant, located in the southeast part of the City, there is a group of wells drilled on an area of ten acres. Well No. 10 is a 16-inch diameter well with an original total depth of 655 feet. Several years ago this well collapsed and was filled to a depth of 300 feet from the ground-surface. The perforations in gravel down to this depth are 85 to 95, 226 to 231, and 262 to 282 feet. This well had 12 cuts to the circle every eight inches with a 1/2-inch by 4-inch Mills Knife. Assuming all perforations to be perfect, the area of perforation would be 7.33 square feet. The normal water-table during this experiment was 93 feet from the ground-surface as determined by a water-stage recorder.

A continuous flow of water was started into this well on March 4, 1933, and was shut off on June 5, 1933. During the three-month period this well took 2,070,350 cubic feet, or 47.53 acre-feet, and the average head above the natural water-table was approximately 65 feet. Due to the water being taken directly from the street-main it was impossible to keep a constant head because it varied with the consumption throughout the day.

As this plant is located in the center of an industrial district and there are many private wells of large capacity in operation, the water-table throughout the day varies considerably and for this reason the effect of the spreading on other wells was impossible to follow.

Over the spreading-period of 92 days the average rate of percolation was 116.9 gallons per minute, or at the rate of 15.948 gallons per minute per square foot of perforated area.

In the southwesterly part of Los Angeles is a plant known as the Manhattan Pumping Plant. The water-bearing strata in well No. 4, all of which are perforated, are 252 to 310, 360 to 388, 420 to 426, and 446 to 510 feet from the ground-level. The total perforated area, assuming all cuts to be perfect, is 34.17 square feet. The casing is 16 inches in diameter, with a total depth of 625 feet. When pumped it delivered 900 gallons per minute, but occasionally broke suction, with a drawdown of 93 feet from the standing level of 72 feet.

During the spring of 1934 an experiment was carried on to determine the effect of head on the rate of percolation. A flow-meter was attached to the inflow-line and by means of a six-inch stilling-well placed in one side of the casing, a float giving the elevation of the water-surface in the well was installed.

Due to the fluctuating pressure, caused by varying domestic consumption throughout the day, both the meter and gage on the stilling-well were read hourly and the inflow regulated so that a constant head was maintained throughout the duration of each period of the test. Starting with a head of ten feet above the static water-level of 72 feet, the head was increased by five-foot intervals until a maximum of 70 feet was reached.

In acre-feet per day the percolation increased from 0.2502 for a ten-foot head to a maximum of 0.6620 with a head of 70 feet.

The maximum safe percolation head on this well should be taken as 65 feet. At this head the percolation-rate is 4.22 gallons per minute per square foot of perforation. Using the discharge of 900 gallons per minute (at which point it broke suction), the pumping capacity is at the rate of 26.34 gallons per minute per square foot of perforated area. A comparison shows that the spreading-rate of 4.22 is only 16.02 per cent of the pumping capacity of 26.34 gallons per minute per square foot of area.

The Slauson Well, with a head of 65 feet, has a percolation-rate of 0.245 gallon per minute per square foot of area per foot of head. The Manhattan Well, with a head of 65 feet, had a percolation-rate of 0.065 gallon per minute per square foot per foot of head, or only 26.53 per cent of the rate obtained at the Slauson Well. A part of

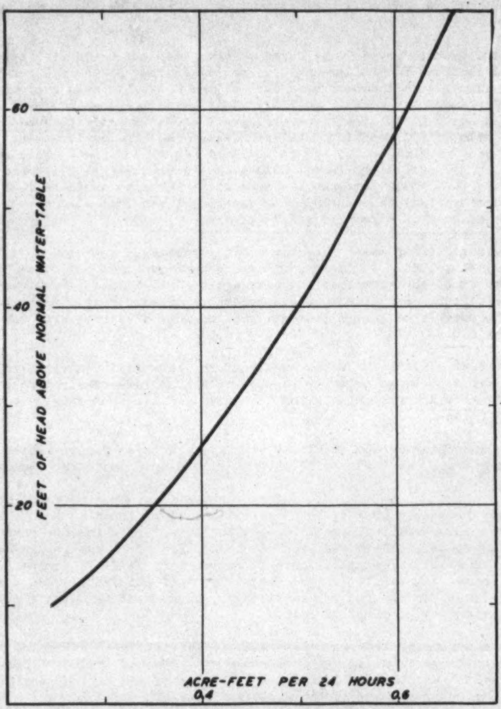

FIG. 1—EFFECT OF HEAD ON RATE OF PERCOLATION ON MANHATTAN PLANT WELL NO. 4, 1933-34 (DEPTH, 625 FEET — DIAMETER, 16 INCHES)

this difference in rate may be attributed to the coarser materials found in the Slauson Well. However, it is believed that the factor most affecting the percolation is that in the Manhattan Well the water-table stood up within the clay blanket. At the Slauson Well the upper perforation was from 85 to 95 feet with a water-table at 93 feet. The gravel-material in this upper stratum, however, was from 45 to 95 feet, which gave the water an opportunity to percolate freely up into this dry area.

Salient factors to be considered in spreading by means of wells are: The water must be clear and free from matter which would promote the growth of bacteria; the rates of percolation will be affected by the head applied above the natural water-table; whether the perforations are into a dry stratum or one containing water. Frequent surging of the wells by blowing with an air-compressor will materially increase the percolation-rate.

Underground water-spreading by means of wells is similar to the developing of ground-water supplies, in that each area, if not each individual well, must be considered as a separate problem. The results obtained in one district cannot be applied in its entirety to any other district. General conclusions drawn from any particular area, however, may safely be applied to this type of spreading.

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MAINTENANCE AND OPERATING PROBLEMS OF WATER SPREADING-GROUNDS, SOUTHERN CALIFORNIA

K. Q. Volk

Maintenance and operation of water spreading-grounds as a means of increasing local water-supplies in Southern California is complicated by the fact that the streamflow in the spreading-season or winter months is flashy in character and of short duration. During high flows the streams frequently carry large quantities of silt and debris which should not be diverted onto the spreading-grounds unless provision is made for settling-basins, or the spreading-grounds are of such character as not to be harmed by silt unless carried in excessive quantities. Table 1 shows the runoff of Big Tujunga Creek recorded by the Los Angeles County Flood Control District. This Creek is typical of many Southern California streams.

Table 1--Runoff of Big Tujunga Creek at Edison Road Crossing, storm of February 8, 9, and 10, 1932

Date	Time	Runoff	Date	Time	Runoff
1932	h	sec-ft	1932	h	sec-ft
Feb. 8	9	100	Feb. 9	12	1060
	12	260		15	1160
	15	760		18	1060
	18	3910*		21	800
	21	1400		24	580
	24	1000	Feb. 10	3	500
Feb. 9	3	900		6	380
	6	980		9	320
	9	1020		15	220

*Peak.

Surface storage-reservoirs are desirable for reducing peak-flows and removing silt. However, many of the streams in Southern California where water-spreading is practiced have small, steep watersheds so that economical surface-storage is not available.

In the past, one of the principal sources of water-supply for the underground reservoirs was channel-percolation as the flood passed over the debris-cone or down the channel of the river. The low summer flows which were diverted at an early date by water companies near the mouths of the canyons have had to be augmented on account of increased irrigation use by pumping from underground basins or reservoirs located on the debris-cones or along the channels of the stream. Many of these underground basins are formed by fault-lines, underground dikes, or barriers.

The spreading-works in the past for each stream were usually sponsored and financed by the local water companies, by individual users, and by cities who derive their water-supplies from the respective canyon or underground reservoir. The maintenance and operation of spreading-works after they are constructed generally falls on the interested water-users, who contribute annually in proportion to the amount of water that they pump from the basin. This method makes for equitable distribution of expense and harmonious relations between the various users. The money contributed by the different interested parties was generally derived from sales of water or assessments of water-users.

Lands--The lands used for spreading water are either rented, owned in fee, or public land set aside for this purpose. The amount of land used for spreading and the capital investment advisable in structures varies widely depending upon the size of the watershed, character of stream-flow, volume of water available for spreading, value of the lands, the cost of the necessary structures, and the area of lands to share in the benefits. The lands should be of an absorbent character, the slopes not too steep, and the volume of the underground reservoir beneath the spreading-grounds large enough to hold the maximum amount of water spread in any one year, preferably large enough for holdover storage for a period of years.

In recent years the State of California, San Bernardino, Riverside, and Orange counties have contributed money for spreading-projects in addition to that contributed by interested individuals, water companies, and cities. During the past two years funds available for relief work through the Civil Works Administration and Civilian Conservation Corps camps have been expended on the spreading-grounds in San Bernardino County.

The Los Angeles County Flood Control District built the spreading-grounds on Big Dalton and Pacoima creeks. Both of these streams have regulated storage constructed by the same agency.

Diversion-dams--Permanent rather than temporary diversion-structures are preferable provided the cost is not excessive. During large flows temporary dams which are generally used to divert only a portion of the flow are washed out and a large volume of the water passes before they can be restored, resulting in a considerable loss of water. Permanent diversion-dams or weirs are frequently constructed on debris-cones built up by flood-discharges in former years where, on account of the depth of the fill, it is not possible to connect the ends or bottom to bed-rock. It is essential that they be capable of passing major floods without being washed out or undermined. These diversion-structures are generally built at right-angles to the stream with the crest level with the stream-bed and equipped with head-gates at one or both ends for the regulation of water diverted.

The diversion-weir on the Santa Ana spreading-grounds is 400 feet in length and cost in excess of $80,000. The canal leading from this structure to the spreading-grounds has a capacity of 1000 second-feet and is equipped with a Parshall flume for measuring the water. On Lytle Creek final plans call for five permanent diversion-weirs along the main channel of the stream, ranging from $10,000 to $25,000 per structure. Flood-flows of 40,000 second-feet have been recorded on the Santa Ana River and 16,000 second-feet on Lytle Creek. On San Antonio Creek three permanent diversion-structures are planned. In the case of Lytle and San Antonio creeks the main flood-channel is carried directly through the spreading-grounds. On Cucamonga Creek the stream is confined between high banks as it leaves the mouth of the canyon and a series of ten horizontal cross-walls constructed of rock and wire have been provided for reducing the velocity of the stream and depositing material in the debris-basins formed between the walls, which are located a short distance above the diversion-dam built at an angle of 45° across the stream-channel and equipped with five sets of diversion-gates.

Distribution-system--A main canal of proper dimensions and grade leads from the temporary or permanent diversion-structure to the spreading-area located either in the bed of the channel or on higher lands adjacent thereto. The distribution-system after reaching the spreading-area should be so designed as to provide as nearly automatic operation as possible. In the case of contour-ditches or basins the flow ought to be divided proportionately by proper structures and regulating gates. Ditches or laterals should be so designed that a larger head of water can be turned through them from time to time for scouring the bottom and removing sand and silt deposited therein. Contour-ditches are generally provided with pipes at intervals through the lower bank and in some cases temporary or permanent checks for spreading water in the area between the ditches. Where desilting basins are provided, provision, if possible, should be made for flushing them periodically into the main stream-channel where the silt will be removed by the larger flows which cannot be economically spread. The desilting basins on debris-cones usually consist of a series of big ponds formed by building a large levee on the lower side and turning both ends back to intersect the slope of the cone. In some cases these levees are 25 feet in height. The clear water is skimmed from the upper portion of the basin and spread on lands below the levee. Frequently they are built consecutively down the slope with the spreading-area between, the canal for supplying the desilting basins being constructed along one or both sides.

On the new spreading-works on Lytle Creek, water in the main canals leading from the diversion-dams is distributed by means of pipes placed through the lower side of the canal into laterals approximately 12 feet in width and two feet in depth running down the slope parallel to the stream-channel. It is estimated that a mile of such ditch will absorb a flow of 300 miner's inches or six second-feet. The ultimate plans call for 500 miles of laterals.

On the Saticoy spreading-grounds of the Santa Clara Water Conservation District the water is carried from two concrete head-gates on the river to the spreading-basins by a 48-by 60-inch concrete pipe-line 2640 feet in length.

Operation--The larger spreading-grounds are generally in charge of an engineer or superintendent who is acting in the same capacity for one of the water companies. He organizes his crew from other water-company employees or local labor. Experienced men for handling water are available for spreading during the winter months when the water companies are not supplying irrigation-water. The number of men employed varies with the size, design, methods of spreading, and volume of water available. A larger crew is required when the water is first diverted and the force reduced as soon as the water is regulated throughout the area. Good roads are essential to efficient operation of spreading-areas.

Care must be taken wherever water is diverted for spreading to see that adequate provision is made to control water diverted so that the same cannot leave the spreading-grounds and start cutting new channels. In many cases highly-developed agricultural lands and cities are located directly below the spreading-areas and a new channel through such a section would cause great damage to property and possible loss of life. The general method of providing protection consists of constructing a levee along the outside of the area used for spreading so as to return excess waters again to the main channel.

Permanent as well as temporary structures (built of rock and wire) should be inspected from time to time to see that they are not undermining or that the wires holding the rock have not been cut. Repairs should be made as soon as the water can be turned out in order to be ready for the next storm.

Suitable measuring devices ought to be installed on the main canals supplying the spreading-area and water returned to the river consisting either of weirs, Parshall flumes, or staff-gages rated by frequent current-meter measurements. It is advisable to equip all gaging-stations with clock-registers for recording the variations in flow. Rates of percolation should be determined for different methods of spreading and various classes of surface material occurring on the spreading-ground to see that the maximum absorption is taking place and in addition the actual areas used be measured. It is advisable to make systematic measurements of water-levels and wells to show the rise of the water-plane due to spreading. Part of this rise may be due to the rainfall-penetration and part to natural percolation in the channel of the stream.

On Mill Creek where the water is diverted by means of a number of temporary dams through a series of contour-ditches, it is estimated that two men can spread the first 100 second-feet, and that it requires one additional man for each 20 second-feet above this amount. The capital investment in lands on Mill Creek amounts to $105,000 and $9000 in ditches and structures.

On the Santa Ana cone up to July, 1933, $227,000 had been expended for lands and structures and a total of 266,784 acre-feet had been spread.

V. M. Freeman, engineer for the Santa Clara Water Conservation District in Ventura County, has kept accurate records of the cost of spreading water during the past two seasons. Table 2 gives the cost of spreading including labor and materials only. This District rents the land used for spreading on Piru Creek, Santa Paula Creek, and at Saticoy. They have found that it is possible to materially increase the absorption-rate in the main channel of the river at the Camulos spreading-grounds where the river-bed is flat and sandy by plowing furrows with a tractor while the water is flowing and diverting the stream-flow into the same; also that the percolation-rate can be increased in the main channel near Saticoy by cultivating with a tractor.

Table 2--Cost of spreading for Santa Clara Water Conservation District

Name of spreading-ground	Type of spreading	1931-32		1932-33	
		Spread	Cost acre-foot	Spread	Cost acre-foot
		acre-feet	$	acre-feet	$
Camulos	Plowing river-bed	903	0.147	565	0.052
Piru	Basin-method	6652	0.143	3100	0.155
Santa Paula	Basin-method	2191	0.217	2008	0.131
Saticoy	Basin-method	9121	0.217	10254	0.096
Saticoy	Cultivating river-bed	....	.....	1273	0.131
Total		18867	0.191	17200	0.112

Spreading has been conducted on the San Gabriel River by the Committee of Nine over a long period of years. Water is diverted by means of a temporary dam through a tunnel in the hill leading to the spreading-grounds. The structures are all of a temporary nature and the undisturbed-brush area has been very effective for spreading both clear and somewhat silty water at a very low cost.

The spreading-project of the Coachella Valley Storm Water District is located directly in the stream-channel of the White Water River. There is no diversion-dam and spreading is automatic. The only structure is a low, wooden and wire dam five feet in height, constructed approximately three feet above the original ground-surface. The debris carried by the first high-water was deposited against the wire fencing and the dam filled to the crest with sand and gravel causing flood-waters to spread out in a thin sheet on the entire length of the dam, thereby greatly increasing the percolation-area. The engineer for the District states that the estimated 1927 flood-peak of 15,700 second-feet was reduced to 3500 second-feet in passing over the spreading-grounds. Portions of this structure have been replaced with concrete on account of the wood and debris deposited by the flood on the fencing rotting after a few years.

Flood-control reservoirs have been constructed on a number of streams in Los Angeles County by the Los Angeles County Flood Control District. Table 3, furnished by E. C. Eaton, Chief Engineer of the District, gives the drainage of the stream, type, height of dam, storage-capacity, rate of percolation in second-feet per wetted acre, and stream-channel below each dam. These percolation rates are the average of the number of measurements.

Table 3--Data for Los Angeles County Flood Control District

Name of dam	Drainage-area above dam	Type of dam	Height above stream-bed	Storage-capacity to spillway	Rate of artificial absorption in channel below
	sq mi		feet	acre/ft	sec-ft/wetted acre
Pacoima	27.77	Constant angle-arch	365	9265	4.39
Tujunga	81.50	Variable rad. arch	200	6250	1.37
Devil's Gate	30.88	Gravity-arch	100	4567	2.60
Santa Anita	10.82	Constant angle-arch	225	1376	3.84
Sawpit	3.27	Constant rad. arch	147	476	8.06
Big Dalton	4.54	Mult. arch	146	1039	2.87
Thompson Creek	3.91	Gravel-fill	66	812	No records

The author is indebted to the following men who are interested in water-spreading in Southern California for information regarding the spreading-grounds with which they are connected: George Hinckley, Francis Cuttle, L. A. Hosegood, Phil Hasbrouck, Morgan Pierce, V. M. Freeman, R. V. Ward, W. P. Rowe, and E. C. Eaton.

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THE DEPLETION OF UNDERGROUND WATER-SUPPLIES

Harold Conkling

During the past almost two decades the underground water-table in almost all parts of California has been lowering. This is due to subnormal replenishment since about 1916 to 1918, and a simultaneous increase in draft. The falling water-table has agitated the entire State and especially all water-users who are largely dependent on underground water for their irrigation-supply and has given rise to these questions: (1) Is this recession caused by cumulative overdraft which eventually will cause permanent reduction of irrigated area in any particular valley unless new water is imported or local wastes conserved; and (2) can new water be imported to any particular area or local water conserved in that area at feasible cost.

Since 1916, runoff up to October 1933 into Southern San Joaquin Valley and into the coastal valleys of Los Angeles, Riverside, San Bernardino, and Orange counties has been about two-thirds of the long-time average. In the west-coast valleys between San Francisco and Los Angeles, runoff during that time has been about 55 per cent of the long-time average. These are the general areas in which the recession of water-table has been most severe.

During the period there has been an enormous increase in the area irrigated by pumping in California. It seems probable that the area so watered was not greatly larger in 1916 than it was at the time of the preceding United States Census. In the interim most years gave above-normal rainfall, gravity-supplies were large, and the expense of pump-installation would not be undertaken so long as the irrigator could get by without it. Likewise it is thought that there has been no great increase between the 1929 census and the present date, and that the area irrigated from underground water was about the same as that at present so irrigated. No study has been made to verify these beliefs and for the purpose of this paper they are accepted. The census of 1909 does not give the acres irrigated in the State by pumping but it does give the number of pumps installed. The census of 1929 gives both the acreage and the number of pumps. It is assumed that the number of pumps is a rough index of the acreage irrigated. In 1909 there were 7100 pumps. In 1929 there were 36,300--an increase of 411 per cent. Disregarding everything north of San Francisco, it is found that the distribution of pumps in the areas discussed in this paper was as shown in Table 1.

Table 1--Distribution of pumps for various areas

Area	1909	1929	Per cent increase
San Joaquin Valley...	3322	25436	665
Santa Clara County...	587	2516	330
Monterey County......	124	855	590
Ventura County	126	823	554
Los Angeles County... San Bernardino County Orange County........ Riverside County.....	2601	5663	118

In a period during which runoff has been from 33 per cent to 45 per cent less than the long-time average, use has increased twofold in Southern California, almost sevenfold along parts of the west coast, and almost eightfold in southern San Joaquin Valley.

Either the increase in use or the decrease in supply alone would have caused recession, for every change of input or draft must be reflected in change of the water-table, as an underground reservoir of course obeys the same law as does a surface-reservoir.

For the sake of clarity, the hydrology of the underground basins in California will be briefly discussed. Each of those in California is supplied by percolation from the streams which cross them and by direct deep percolation of rainfall on the valley-floor. The supply therefore varies with the cycle of rainfall. This supply must be disposed of. In nature it was disposed of mainly by evaporation from seeped lands in the lower parts of the basin, by flow of rising streams into the Ocean, and in some cases no doubt by underflow to the Ocean. Disposal is more uniform than input which varies from season to season, year to year, and cycle to cycle so that the water-table has at all times been in a slow state of fluctuation.

When irrigation begins a new draft is put on the basin, but at the same time natural methods of disposal continue. The water-table must lower with comparative rapidity until the natural methods of disposal cease to act or are diminished as far as practical. If the irrigation-draft on the average does not exceed the diminution in natural disposal, there is no cumulative overdraft but there is a permanent lowering of the water-table which will forever cause greater cost in procuring water than was incurred when the basin was first tapped by pumps. If the cost becomes too great, the marginal users will go out of business and the average water-table will rise somewhat, thereby decreasing costs to all remaining although this decrease may be only infinitesimal.

If, on the other hand, irrigation-draft exceeds long-time average natural disposal, the basin is overdrawn. It then becomes certain that the water-table will continue to recede and cost of water will continue to increase until sufficient water-users have been forced out of business so that there is no overdraft. The matter is self-adjusting. The difference between a lowered water-table due to a cycle of drought and a lowered water-table due to draft in excess of average replenishment is one of degree. Certainly a greater number of individuals will be ruined in the latter case. In neither case, however, can the matter be helped unless water can be imported or locally conserved at less cost to the user of irrigation-water than the cost which caused him to abandon his enterprise. This is an important point not often stressed in plans for conservation. The term "cost" as used above may be taken to include all intangibles.

For the short term of years in which the water-table has been under observation in California there is no way to definitely distinguish from observation of the water-table alone whether there is or there is not a long-time cumulative overdraft, although in certain cases an almost definite conclusion may be reached. As a practical near-future matter, however, it may not be important whether there is cumulative overdraft or not. Even if overdraft exists, the increase in cost of securing water may be so gradual and the limiting cost so far in the future that it is of no practical immediate consequence. In other words, if the overdraft is not too great, the banker may loan and the farmer go on in his present way with a secure feeling on the part of one that his loan is safe for its lifetime and on the part of the other that he need incur no capital expense for a term of years to secure an additional supply. In the long view, however, determination of cumulative overdraft is vitally important if along with it goes a plan for importation of outside water or conservation of local water to give information as to cost of present underground supplies compared to that of new supplies.

So much for the matter in general and its interesting economic implications. The remainder of this paper is devoted to a description of the work of the California State Division of Water Resources, the general methods employed in analyzing the situation in various parts of the State, and the conclusions as to overdraft reached therefrom. Necessarily the paper deals only with the situations found in California, and the methods used are applicable only in similar situations.

The work of the California Division of Water Resources on underground water in the State has covered practically all areas with various degrees of intensity where underground water is important. It has embraced the Great Central Valley with particular reference to the southern end, Napa, Santa Clara, and Salinas valleys along the west coast, and the coastal valleys of Ventura, Los Angeles, San Bernardino, Riverside, and Orange counties. With the exception of Napa Valley where water-supplies are drawn largely from the igneous rock underlying the valley-fill, and a portion of Ventura County where the supplies are drawn in part from the older consolidated sedimentaries underlying the recent alluviums, the formation from which water is drawn in the various valleys is practically the same, that is, it is drawn from recent deposits whether of fluvial or marine origin. Consequently the experience of the Division is almost entirely in that phase of underground waters and does not extend to formations such as are found in some areas of New Mexico, for instance, where supplies are secured under pressure after having travelled long distances from the point of origin through channels in the country rock.

The problem in California is somewhat simpler, it is believed, than it is under the complex situation just noted. Sufficient well-drilling has been done in all the alluvial valleys of the State to delimit the areas where water-bearing formations exist sufficiently porous to give yields for irrigation. The problem then is to develop methods to determine the safe yield of a valley or a basin in a valley, assuming that the recorded rainfall is indicative of the average. What is needed for each determination of course is an accurate evaluation of the average recharge as compared to the draft, and there is also needed in a great many areas an evaluation of the capacity or specific yield of the underground basin.

The most intensive work has been done in southern San Joaquin Valley and in South Coastal Basin (Orange, Riverside, Los Angeles, and San Bernardino counties). The methods used vary considerably in detail and are believed applicable to other basins. The South Coastal Basin methods have been applied to Santa Clara Valley, Salinas Valley, and Ventura County. The two methods of determination of cumulative overdraft are briefly described in the following paragraphs.

San Joaquin Valley has an extremely light rainfall. Practically never does rain penetrate past the root-zone and to the water-table. The amount of water used for irrigation each summer is almost the same no matter what the winter rain may be in the valley. Most of the underground basins are closed, that is, there is negligible underground flow out of them and the same is true of the inflow. Almost all inflow and outflow are measured and reliable evaluation of the supply can be made each year. For study the portion of the Valley in which pumping from underground is possible was divided into ten units from Madera on the north to Bakersfield on the south. The change in water-table has been reliably recorded in each every fall, in some cases beginning with 1917 and in all cases with 1921. Areas irrigated each year in each unit are known. Platting for each unit the net annual inflow per acre irrigated each year against the change in water-table for that year results in a remarkably definite curve which indicates in most of the basins that if two acre-feet of stream-flow per acre irrigated are retained in the basins the water-table will not change. In other words, the net use is two acre-feet per acre irrigated. This of course includes unmeasured losses and probably the actual consumptive use in irrigation is in the neighborhood of 1.8 acre-feet per acre irrigated. If the net inflow for a year is less than two acre-feet, the water-table is lower in the fall than it was the preceding fall; if more than two feet, it is higher. It seems safe to assume that the amount added to or subtracted from the underground basin is the difference between the two acre-feet of consumptive use and the net recharge or depletion. Therefore, if this difference is multiplied by the irrigated area and divided by the gross soil-volume filled or drained, the result gives the percentage of drainable voids in the valley-fill or, in technical language, the specific yield.

As stated, most of the basins are known from a study of the formations of the valley-fill to be closed. In the Madera and Kaweah units especially the apparent net use is greater than two acre-feet per acre. In both of these, geologic study indicates that there is a probability that a greater amount escapes the unit underground than is the case with the other units, and, furthermore, there exists in them greater areas of seeped land and a greater amount of native vegetation using water along streams. It is believed that these causes account for the apparently greater net use per acre in these units and that actually the consumptive use is not greater than in the others.

The specific yield as thus determined in San Joaquin Valley varies from a low of 7 per cent in the Lindsay area to 20 per cent in both the Fresno and Madera areas. This is in line with what one would expect as the deposits of the larger streams should give the most permeable material.

For the 20-year period ending 1929 cumulative shortages are found in the Madera, Kaweah, Lindsay, Tule Deer Creek, Earlimart, McFarland, and Edison areas. For the 40-year period ending 1929 the shortages are somewhat reduced and are confined to Madera, Lindsay, Earlimart, and McFarland areas. However, recession of the water-table has been so great in the other units as well as in these that costs have been increased to the point where water can be brought in as planned in the Central Valley Water Project at less than present costs to the water-users in the long run.

In the foregoing the estimate of specific yields is an interesting matter, but it is not necessary to the determination. Inflow, outflow, change in water-table, and area irrigated are definitely known in sufficient number of areas to provide a basis for definite evaluation of shortage.

In South Coastal Basin the situation is different. In San Joaquin Valley the average rainfall varies from 5 inches to 11 inches according to location, but in South Coastal Basin it varies from 14 inches to 26 inches, thereby causing percolation to the water-table which occurs only to a negligible amount from rainfall in San Joaquin Valley. In the Valley the basins are generally closed, but in the South Coastal area they are generally not closed and there is underflow from one to another. In the Valley the crops raised in most areas are similar, but in the Basin there is an extreme diversity of crops. In the Valley the net inflow to each area can in most cases be determined easily and with considerable accuracy, but in South Coastal Basin even the net inflow from streams is not accurately determinable, penetration from rainfall is even less certain, and amount of underground flow is entirely indeterminable by direct means. Total runoff into the Basin and out of it into the Ocean is of course accurately measured, and this is true of the rainfall on the valley-floor also. That is, net water arriving at the alluvial basin as a whole or the major parts of it are known as is also the surface-escape from the major upper areas to the lower and from the lower to the Ocean. At least one more quantity must be known to approach the determination of shortage with certainty, and this quantity is the specific yield of each of the various underground basins so that a change in water-table can be evaluated in terms of acre-feet. This is an essential item in the equation and not a by-product of the equation as was the case in San Joaquin Valley.

The alluvial valleys of South Coastal Basin are divided into 29 basins, separated either by hills, mountains, or subsurface barriers, or in some cases indefinitely by different sources of supply. Each basin must be studied separately, but this adds only to the labor of the problem as conditions between basins differ only in degree. This multiplicity of basins is important in the practical application of the results found by the investigation but not to the method. Each one of the basins is a reservoir not essentially different from a surface-reservoir. The capacity of a surface-reservoir can be determined without a survey if the inflow, outflow, and change in water-level are measured over a sufficient length of time. As a matter of practice the capacity is never determined that way but rather by a detailed topographic survey. The yield of the reservoir is determined by the inflow and draft.

Similarly the capacity of an underground reservoir can be estimated by the rise or fall of the water-table compared to the balance of inflow and outflow. In this case the method is even more unsatisfactory than it would be for a surface-reservoir because of the difficulty of evaluating inflow and draft. However, if the capacity between any two levels can be found by other means, an extremely valuable aid and check will exist for all computations of input and draft and the limit of probable error is narrowed considerably. The unconsolidated water-yielding materials in South Coastal Basin and most valleys of the State are coarse and lend themselves to such determination.

Determination of voids in the valley-fill from which the commerical water-supplies are so largely drawn rests primarily on study of well-logs, interpretation of the drillers' notes, and mechanical analyses of samples. The State has been fortunate in the courtesy of Pomona College which made available a large amount of space and equipment for a laboratory. The method of procedure was as follows.

About 5000 well-logs were studied and it was found that the material was classified as clay, sandy clay, sand, coarse sand, gravel, and coarse gravel. These logs were made by many well-drillers, and the classification of no two drillers is exactly the same nor is the classification of the same well-driller in one area the same as in another having different characteristics. In the laboratory, mechanical analyses of many samples from cut banks, dug wells, and exposed surfaces were made in the usual way to get the percentages of different sizes in the material. Experiments were made to determine voids in various typical samples. Finally it was found that the percentage of voids in measured samples could be correlated from the mechanical analyses, with materials in place or reported in well-logs, most easily and definitely as a function of the maximum 10 per cent grade-size, that grade-size being the one in which the cumulative total beginning with the coarsest material reaches 10 per cent of the total sample. This is generally one grade-size larger than the dominant by weight coarse size.

The retention of water by alluvium is inversely proportional to the size of its particles. Clay will retain it all and gravel will yield most of it. Determinations of specific retention were made and related to the same grade-size used as the guide in determination of voids. A graph has been made showing the specific retention and the voids, platted against the 10 per cent maximum grade-size, the difference between the two curves being the specific yield.

The object of this laboratory work was to provide a reliable estimate of the specific yield at any depth and in any location. The laboratory work must be modified by an element of judgment in its interpretation and judgment is especially demanded in interpreting the drillers' logs. An important feature in guiding the judgment is the slope of the streams in their mountain reaches. Velocity of water is most important in determining size of particles moved. Cones formed from steep canyons are also steep. Most of the streams from steep canyons in South Coastal Basin are small but the material at the apices of their cones is, as a result of the velocity of the water issuing from them, coarser than that from large canyons. As the amount of water is small, it is generally dissipated by percolation soon after it reaches the valley; consequently, the cones do not extend for great distances. There is more clay in the cones of small streams than in those of large streams. The clay was not laid down by the stream but is the result of weathering of the original gravel-deposits. The small streams often entrench themselves in their cones and thus may stay in one location for many ages giving the undisturbed portions of the cones a chance to alter. For instance, there is about as much clay as there is gravel in the smaller cones on the west of San Gabriel Valley, but in central San Gabriel Valley dominated by San Gabriel River itself clay is only about 15 per cent of the total valley-fill. Depth of material below the surface is a factor, for due to pressure the voids will be smaller at considerable depths than at the surface. All in all, the various data available require judgment in their use, and to the extent that this is required the result is liable to inaccuracy. However, errors in assumption fairly made have a way of balancing and it is the belief that a sufficiently reliable estimate has resulted.

In order to determine storage-capacity values, the logs were grouped in groups of two to twelve logs each, their materials averaged, and specific yields computed by vertical intervals in each group. For final estimate the entire area was divided into small quadrangles of 252 acres and specific-yield values for each, by 50- or 100-foot vertical intervals, was interpolated from the well-log group-values. A map has been drawn on which contours of equal yield have been drawn for the zone 50 feet above to 50 feet below water-table of fall of 1931. Minimum specific-yield values of four and five per cent are recorded along the basin-margins where the cones are steep, and maximum specific-yield values of 16 to 20 per cent, in the central, fairly flat parts of the valleys where large streams have deposited most of the materials. This shows plainly the increase in voids with distance from the mountains and with increase in size of streams.

Final estimates as to overdraft have not been made in South Coastal Basin nor has final detail of methods been evolved. It appears that in some basins the change in storage will be the only criterion available and that in others other data can be used.

Preliminary calculations indicate that areas of cumulative overdraft are found in the small basins around the margin of San Gabriel Valley, in the western arm of Santa Ana Valley, in Orange County the underground basin of which is dominated by Santa Ana River, and in the west coast south of Santa Monica.

The same procedure was followed in Ventura County, where possible. The only areas of possible present cumulative overdraft were found to be those in the southern part in the valleys of Calleguas Creek. Water-supplies here are derived from the Saugus formation, a soft porous sandstone forming the watershed and underlying the recent alluvium. With present knowledge no evaluation of the recharge or of the voids can be made, and no definite conclusions may be drawn. It does appear probable, however, that Simi Valley and the eastern part of the coastal plain known as Pleasant Valley are overdrawn.

A much less intensive investigation of Salinas Valley was made. It appears that with the lettuce acreage of 1931 there was only a slight margin of safety against cumulative overdraft. Lettuce acreage has decreased about 75 per cent since then and danger of cumulative overdraft has disappeared at least for the time being. Lettuce growers have been pumping over six acre-feet per year and practically all the acreage has been in the artesian area where there is no return of the surplus water to the water-table. It is probable that as good crops would be raised by pumping about two acre-feet. If this modification were made, there would be a considerable margin against overdraft even if the former acreage of lettuce were again planted. In this case, education appears to be the most economical method of providing for the situation.

In Santa Clara Valley the general area west of San Jose and also an area along the east side of the Valley show evidence of cumulative overdraft. In the remainder of the Valley the evidence points the other way.

Inland for some distance from the present ocean-front for considerable distances in most basins bordering the Ocean, the subsurface deposits were laid down under water, and as a consequence there are found almost continuous strata of blue clay as distinguished from the discontinuous lenticular beds of yellow and red clay found further inland where the Ocean has not influenced deposition. In such areas of continuous strata the water is found under pressure. In some areas flowing wells exist. Similar but much smaller areas of artesian pressure are found just above the subsurface barriers of the interior basins in South Coastal Basin. In these areas there have been very marked recessions of the water-table, but this is due to reduction in pressure caused by the increase in number of wells tapping the artesian aquifers and does not indicate depletion of underground storage in the vicinity. The drop in pressure at these wells has sometimes been spectacular and apparently it has been believed by many that there is a corresponding actual depletion.

A potentially destructive result of the lowering of pressure along the ocean-front is intrusion of salt water to the pumping strata, and this has caused great concern as in some areas, notably in South Coastal Basin and Santa Clara County, the pumping level and in some cases the static levelare below sea-level.

The last survey available indicates that water is being pumped from below sea-level in an area of 162 square miles along the coast in South Coastal Basin and sodium chloride has been reported in many wells. However, more detailed analyses by the Division indicate that most of this salt is from intrusion of water from oil-wells into the pumping strata and that there are only a few wells and those in a small area actually showing intrusion of ocean-water. The bulk of the area is protected by a subsurface barrier, but even outside the barrier intrusion is small. In Santa Clara Valley no certain intrusion has been found, but investigation by the Division has not been intensive here.

There is a recognition by the National Government and by state governments that continuous measurements should be made of streams to determine runoff. In California the stream-measurements give only about half the needed information because so much of our economic development depends on ground-water, which of course depends for replenishment on stream-flow but also on local rainfall. There is no recognition on the part of the National Government of the necessity of continual observation of water-table in such places as California nor is there recognition of such necessity by the State itself. True, the State makes appropriations for investigations which include such information, but when the investigations are concluded funds are not available for continuous measurements. Local organizations are carrying on the work in most places in a lively way at present, but this has been the case before, only to have interest languish as time went on. There should be a definite recognition of its necessity; the information should be gathered and made public at appropriate intervals by some organization such as State or Government. We could proceed with more accurate planning if this were the case.

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DISCUSSION OF "THE DEPLETION OF UNDERGROUND WATER-SUPPLIES"

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Underground water-basins are of three classes--gravity, pressure, and a combination of gravity and pressure. Pressure-classes are of two types, one with the overlying confining medium consisting of overlapping layers and lenses of impervious material and the other with a continuous blanket of impervious material as the confining medium.

Most of the underground water-basins of California are found in alluvial deposits of stream-channels or in the debris-cones below the mouths of the streams. The basins in stream-channels are generally of the gravity-class, while those in debris-cones are generally a combination of gravity- and pressure-classes. The pressure-class is usually found near the foot of the debris-cone, while the upper or catchment portion of the cone is of the gravity-class. The material overlying the confining medium of a pressure-basin is also of the gravity-type.

In discussing the depletion of these basins, we only need consider that portion of the basin in which voids are created due to the exhaustion of the water. In the pressure-class of basin encountered in country rock, the voids are generally created at a considerable distance from the artesian well, in some instances over a hundred miles, so that it is almost impossible to actually measure the amount of the depletion in this class of basin.

It is obvious that no void spaces can be created in a pressure-basin whose confining medium is the impervious blanket (neglecting the overlying gravity-class of basin), until the water-plane has been lowered below the bottom of this impervious stratum and voids created in the pervious stratum. For example, if the bottom of the confining impervious bed is at a depth of 100 feet below the surface, no void spaces will be created until the water-plane is lowered below this level.

The underground water-basins in the south San Joaquin Valley are of both the gravity- and pressure-classes, although by far the greater portion of the water-supply is secured from the gravity-class. The pressure-basins are generally found along the foot of the debris-cones constituting the underground water-basins, and because gravity-water from stream-flows is generally available in those areas north of Tulare Lake and Kings River, it has not been necessary to draw upon this class of underground basin to as great an extent as in the gravity-basins. In the vicinity of Tulare Lake and southerly thereof extensive developments of the pressure-basins are being made.

The main supply to the gravity underground water-basins in the San Joaquin Valley is from two sources, (1) seepage from stream-channels, and (2) seepage from canals and irrigation-water applied on overlying lands. Direct penetration from rainfall occurs at such infrequent intervals as to be negligible except when dealing with specific years. The slope of the land is generally flat and the water-table more or less parallels it. Regarding the basins in the San Joaquin Valley the author says, "Most of the underground basins in the San Joaquin Valley are closed, that is, there is negligible underground flow out of them and the same is true of the inflow." This holds true as to the closures of the lower portion of the basins, but laterally the basins overlap and coalesce in the same manner as the alluvial fans were laid down. However, these basins can be treated as separate units, because the main source of supply for each unit is generally effected and controlled by one irrigation company supplying water to the overlying land in its unit. As long as the stream-channels crossing these alluvial fans are fed by return irrigation-waters, thereby creating a rising stream, these streams act as natural lateral barriers, but as soon as the water-plane in adjacent lands is lowered below the water-level in the stream, so that seepage-loss occurs from the stream, the barrier-effect of the stream is lost.

Bulletin 29 of the State Division of Water Resources, State of California, contains a very intensive study of the basins in the south San Joaquin Valley. Observation-wells on which this study is based are shallow and the test-wells within the pressure-portion of the basins are usually shallow auger holes, so that the gravity-water depletion is measured and not the pressure-depression. The author mentions a method of determination of depletion, consumptive use of vegetation, and specific yield in these basins. This was a method first published by Professor S. T.

Harding (Ground-water resources of the southern San Joaquin Valley, Bull. No. 11, State of Calif., Div. Eng. Irrigation), and appears to be reliable when the average of several years is considered.

The maximum stream-flow in the San Joaquin Valley occurs from melting snow in the High Sierra during May and June of each year, and consequently canal-diversions are greater during these months. The result is that there is very little pumping in the area during this period and the water-levels are at their maximum height at this time. In the method for determining depletion, consumptive use, and specific yield mentioned by the author, the writer believes that the figure of two acre-feet per year for consumptive use and other losses, obtained by this method, is not the correct one.

Economic conditions have a great effect when considering this method of determining consumptive use. Prior to the installation of pumping plants the irrigator was restricted to canal-supply for his entire water-supply, and during periods of shortage he had to decrease his amount of irrigation-water. However, with the advent of pumping plants he is able to apply water whenever he thinks he needs it. If the price for his produce will warrant an increased yield by the application of larger amounts of water, the rancher will pump a larger amount, thereby increasing the consumptive use, in that the water is applied during a portion of the season when there was formerly a deficient gravity-supply. This is well illustrated by a study of individual years which determined the average trend for deficiency and consumptive use in the diagrams mentioned by the author. The writer believes that this economic factor is one that should be considered in determining the amount of water which these lands need. He believes that if prices warrant it, consumptive use by vegetation will be increased and thereby create a deficiency which is not apparent at present. A study of the data contained in Bulletin 29 shows that during the season 1926-27, the average use on 770,000 acres of land was 2.3 acre-feet per acre. This was a season with an average of 12 inches of rain during the winter season and direct penetration of rainfall to the water-table undoubtedly occurred.

Secondly, because of the closed nature of these basins at the lower end, due to the fineness of the material and flatness of grades, some consideration should be given to an escape of water sufficient to maintain the salt-balance in the area. In this respect, Kings River offers an example of what can occur in a typical area in the San Joaquin Valley, or in any other irrigated area. The water from Kings River is probably one of the purest in the world for a stream of its size. Before any water was applied to the Fresno and Consolidated Irrigation districts, the water-table was from 40 to 80 feet below the surface and there were extensive wheat fields at the lower ends of the areas. When irrigation-water was applied the water-table rose, and the former wheat fields became highly alkaline and unfit for any crop production, and were used only as pasture lands. With the lowering of the water-table in recent years by pumping, it has become possible to flush these accumulated salts from the lands and put them in production again. However, the fact remains that even the pure water of Kings River, after leaching through the soil in the area and picking up the soluble materials from both the soil and applied fertilizer, became too salty for crop production when permitted by evaporation to deposit its salt-burden on the surface at the lower end of the area. The writer believes that if any attempt is made to re-use the underground waters of any closed basin to such an extent that no salts are carried away by escaping ground-water, the inevitable result will be the destruction of the fertility of the land by the salt-accumulation.

In view of the foregoing, the writer believes a supply of 2.5 acre-feet per acre is a more correct figure to be used in computing the necessary water-supply for the San Joaquin Valley. The depletion in these areas can be offset by the consummation of the Central Valley Water Plan.

Nearly all of the 29 underground water-basins mentioned by the author in the alluvial valleys of the South Coastal Basin are of the combination gravity- and pressure-type. The writer takes exception to the author in his statement that, "Each one of the basins is a reservoir not essentially different from a surface-reservoir." In any study of the depletion of these basins consideration must be given to pressure-conditions.

A combination gravity-pressure class of underground water-basin may be more correctly likened to a surface-reservoir and its network of distribution-mains. As long as the pipes are full there are no voids created in the distribution-mains, although the pressure may be so reduced by a draft in excess of supply-capacity that the service-taps yield very little water. The draft is correctly measured by the fluctuation of the water-surface in the reservoir. However, there is generally a gravity-supply in the upper horizons of a pressure-basin, and fluctuation of the water-level in this region will correctly record draft and supply in this portion of the underground water-basin.

Unlike the observation-wells in the San Joaquin Valley, which were mostly abandoned wells or shallow test-holes, the observation-wells in the South Coastal Basin are drilled wells, in many cases equipped with pumping plants, and in a majority of cases located near pumped wells. Where pressure-conditions exist, the writer believes that the highest water-level each spring is the best method for comparing water-level fluctuations in these Southern California basins, as the pump-cones have been ironed out and the supply-effect is stabilized. Furthermore, only those observation-wells which record the surface gravity-water supply should be used in studying depletion, as it is obvious that there can be no depletion unless voids are created.

Before any conclusions can be drawn as to the existence of overdraft in any of the basins in the South Coastal Basin, the existence of pressure-conditions must be taken into account. In a water-system when pressures become low along the pipe-line, due to increased draft on the pipe-line from service installations, the condition can be remedied by installation of larger mains, but in the case of a pressure-area there is no possibility of doing this. The only way that the supply can be increased is by steepening the pressure-gradient through pumping the water-levels to lower depths or by gaining the same effect through increasing the pressure-head in the supply- or gravity-portion of the basin by the storage of additional water therein. Actual deficiencies in these basins can be remedied by the importation of additional supplies, but care should be exercised to prevent the importation of water of inferior quality. The present source of supply from return irrigation-water is salty enough without any further aggravation.

In closing, the writer cannot help but comment on the oft-repeated statement that the money "wasted in costly litigation" could be better applied in studying the problem from an engineering viewpoint and spending this "wasted" money in constructive works. He wishes to point out that practically all of the basic ground-water data and methods of their application contained in the various State bulletins were gathered as the result of litigation, and had there been no litigation these data would not have been available to the engineers of the State. He also wishes to call attention to the fact that these "costly lawsuits" have resulted in advancing knowledge of underground water-phenomena many years. The State of California, in publishing its various engineering and irrigation bulletins, is doing a great service to the engineers in the State by presenting to them in bulletin form the results of prior investigation by private engineers in the various areas. The author need not have any apprehension as to the continuance of well-observation in this State in the future, because, regardless of the bulletins published by the State, there will always be "costly litigation" confronting the users of underground water, and for their own protection these records will be maintained by interested local agencies. The writer recognizes the benefit of these State bulletins in which are published well-observations, but wishes to point out that because of the large area involved, these records must, of necessity, be only general in character.

The author, in his plea for support for the continuation of publication of water-level records by the State of California, similar to the work of the Federal Government on stream-flow records, overlooks the fact that the Federal Government presents only the actual figures, and does not attempt to draw any conclusion therefrom. The writer agrees that the State is probably the best agency to handle the publication of these water-level records, but believes that the activity of the State should stop at this point, leaving the interpretation of the data to the interested engineer. He is probably old-fashioned in his resentment of this suggested encroachment by state-employed engineers on the livelihood of private engineers, but believes a halt must be called at some time if we are all not to become wards of the State or Federal Government.

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THE INTERPRETATION OF WATER-LEVELS IN WELLS AND TEST-HOLES

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A frequent problem in ground-water studies is the interpretation of water-level records obtained from wells and test-pits. Such interpretation is necessary not only to determine the cause of observed water-level fluctuations, but to ascertain whether the water-level in a well represents the water-table or a pressure-surface. The position of the water-table could formerly be determined with reasonable accuracy by observing water-level in shallow domestic wells. In recent years, with the increased demand for ground-water, wells are being drilled to greater depth, and at the present time water-levels more frequently represent the pressure-level of confined ground-water than they do the water-table.

With favorable conditions, including shallow depth to water-table and ample funds, it is sometimes possible to supplement existing wells by use of test-pits and auger-holes. Under ordinary circumstances this is not possible, however, and dependence must be placed upon well-observations. It has thus become necessary to distinguish between water-table and pressure-level observations, and in the preparation of water-table contour-maps to eliminate pressure-levels from the basic data. The failure to do this may cause errors which will lead to false conclusions on important issues.

The development of automatic devices for obtaining continuous graphical records of water-level in wells has been of great aid in the interpretation of water-level data. These graphs show fluctuation in minute detail and have been found to delineate patterns which can be identified and classified.

The purpose of this paper is to point out some of the differing types of fluctuation and to present a background of hydrology which will serve to explain the causes of these differences. The writer has had opportunity for practical research in this field, and presents some of the basic data upon which conclusions are based.

Classification of natural materials

The material composing the Earth's crust may be broadly classified as rock and earth. Rock includes all firm hard material occurring in large solid masses. Its porosity is generally low, the voids which contain water being ordinarily represented, either by jointing and fracture planes or by solution cavities. Earth, on the other hand, is the softer unconsolidated portion of the Earth's crust and usually overlies the rock. It is more porous than rock. The water contained in the voids of the more permeable classes of earth is the principal source of economic ground-water.

The elementary forms of earthy deposits are classified as either coarse-grained or fine-grained. The coarse materials include sand, gravel, cobbles, and boulders. Fine-grained materials include silts and clays. Silts are composed largely of rock-dust and flour produced by rock abrasion and impact, together with small particles of resistant minerals released by decomposition of surrounding materials.

Clays are composed of very fine particles, many of them of colloidal dimension, having either granular form with crystal and irregular faces, or scale-like shapes. These particles are the product of rock grinding and impact, and also rock decomposition. Surrounding them is often a colloidal coating, mainly silicious, but which may consist of organic colloids or of the inorganic colloids of iron, manganese, aluminum hydroxide, and hydrated silicic acid. If the colloidal material is in excess, the clay is termed fat, sticky, or plastic; but if the granular matter is in excess, it is called sandy, weak, or nonplastic.

The size classification most generally used in the United States for identification of the various classes of earthy materials and limitation of the fractions separated by mechanical analysis, is that adopted by the United States Bureau of Soils. This classification is also useful as a basis for studying permeability-data. The sizes corresponding to the various fractions are stated for convenience as follows: Fine gravel, 2.0 to 1.0 mm; coarse sand, 1.0 to 0.5 mm; medium sand, 0.5 to 0.25 mm; fine sand, 0.25 to 0.10 mm; very fine sand, 0.10 to 0.05 mm; silt, 0.05 to 0.005 mm; clay (particle), 0.005 to 0.0002±; clay (colloidal), less than 0.0002±.

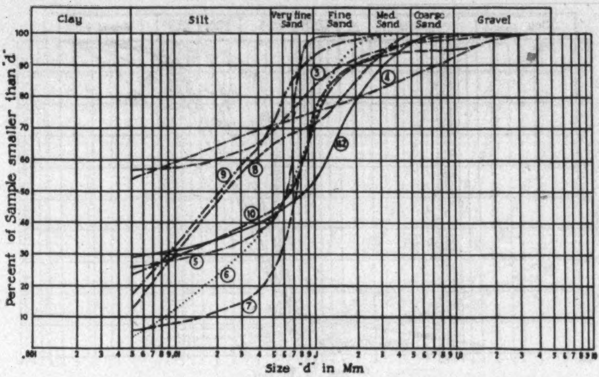

Fig. 1--Mechanical analysis of typical silts and clays--permeability-coefficient 0-2.5

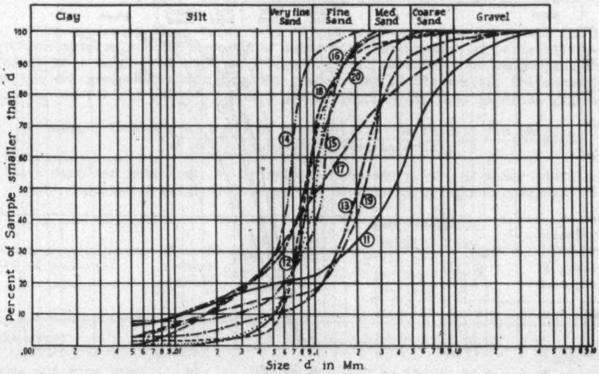

Fig. 2--Mechanical analysis of very fine and fine sand--permeability-coefficient 5-48

Permeability

Permeability is one of the most important physical properties of earthy materials. It controls the movement of ground-water into and out of wells and test-holes, and is responsible for pressure-phenomena in wells.

Permeability may be defined as the property of a rock or earth which permits appreciable movement of subsurface water through it, either when unsaturated and actuated by the resultant force of gravity and surface-pressure of films, or when saturated and actuated by hydrostatic pressure of the magnitude ordinarily encountered in ground-water. Impermeability is the property of a rock or earth which does not permit water to move through it perceptibly under the pressure ordinarily found in subsurface water.

Permeability is defined quantitatively as the rate of discharge through a unit cross-section at right-angles to the direction of flow with a hydraulic gradient of

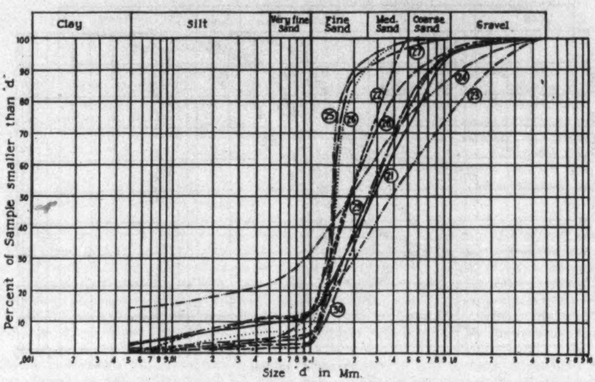

Fig. 3--Mechanical analysis of fine and medium sand--permeability-coefficient 50-250

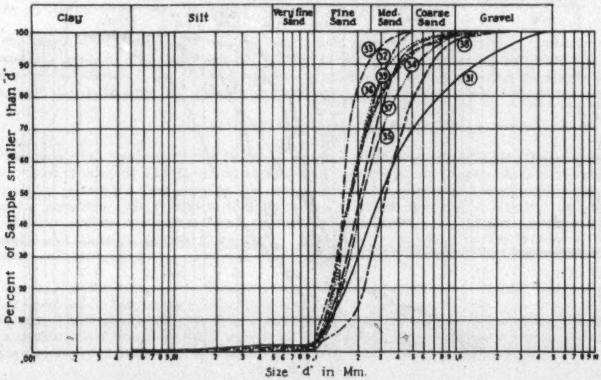

Fig. 4--Mechanical analysis of fine and medium sand--permeability-coefficient 250-700

unity (one foot loss of head for each foot travelled by the water) and at a standard temperature. Using the term "transmission-constant", it has been expressed by Slichter (C. S. Slichter, The motions of underground waters, W.S.P. No. 67, U.S. Geol. Sur., pp. 24-27, 1902) as the discharge in cubic feet per minute per square foot for 100 per cent gradient at 60° Fahrenheit. The term "coefficient of permeability" has come into use more recently and is expressed in various units, that adopted by the Hydrologic Laboratory, Ground Water Division, United States Geological Survey, being gallons per day per square foot for 100 per cent gradient at 60° Fahrenheit is the one used in titles Figures 1 to 5 (N.D. Stearns, Laboratory tests on physical properties of water-bearing materials, W.S.P. No. 296-F, U.S. Geol. Sur., p. 148, 1927). A unit more easily visualized by many hydraulic engineers is the acre-foot per acre (cubic foot per square foot) in 24 hours for 100 per cent gradient at 60° Fahrenheit.

Permeability of saturated undisturbed natural samples can be determined in the laboratory by use of either the constant or the variable-head permeameter. The former

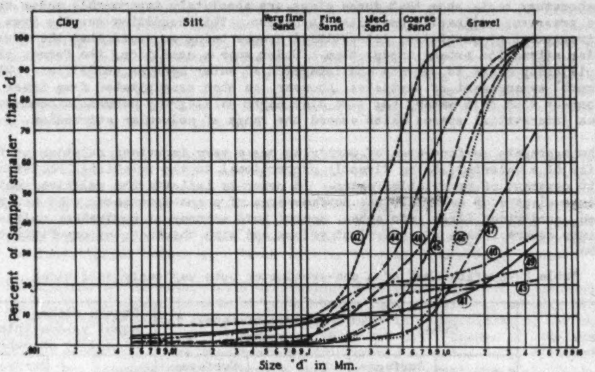

Fig. 5--Mechanical analysis of coarse sand and gravel--permeability-coefficient 800-20,000

is adapted to measuring the permeability of coarse-grained materials, and the latter of fine-grained materials. The results of laboratory measurement of permeability-coefficient of a large number of samples of natural materials are summarized in Table 1. The samples are grouped according to the predominant particle-size, the mechanical-analysis curves for all samples in each group accompanying this paper as Figures 1 to 5.

Table 1--Summary of tests of permeability-coefficient for samples of natural unconsolidated materials

(Data compiled from tests by Hydrologic Laboratory, Ground Water Division, United States Geological Survey, and Pacific Hydrologic Laboratory)

Class of material	No. of samples tested	Relative proportion of silt and clay, % by weight	Coefficient of permeability gals. per sq. ft. per day, 100 % gradient, 60° F		Velocity of flow at 1% gradient, feet per day	
			Range	Average	Range	Average
Silt and clay	10	25 to 71	0 to 2.3	0.53	0 to 0.009	0.0016
Very fine and fine sand	10	6 to 28	7 to 31	16.0	0.03 to 0.10	0.049
Fine and medium sand	19	1 to 11	54 to 662	304	0.02 to 2.0	1.02
Coarse sand and gravel	7	0 to 8	827 to 3788	1845	3 to 12	7.1
Gravel	3	0 to 6	6200 to 20,663	..	26 to 110	...

Examination of the above data shows that for the ordinary range of natural hydraulic gradients, silt and clay are practically impermeable. Medium sand, coarse sand, and gravel, on the other hand, have appreciable permeability and can be classed as aquifers or water-bearing formations. Very fine and fine sand are on the border line, and can be classed as aquifers only when free from silt and clay. It is to be noted, however, that very fine and fine sand can transmit a considerable volume of water when large areas are involved, and may be an important element in producing leakage from earth-reservoirs or canals, or in supplying water to a more permeable underlying formation from which water is being pumped.

Laboratory tests show that dense clays are absolutely impermeable under the hydraulic pressures ordinarily occurring in nature. This condition results from the compact arrangement of particles, interstitial spaces being so small that the forces of molecular attraction extend across them. Under such a condition, the forces of gravity and capillarity cease to operate and interstitial water becomes solidified. With a "honeycomb" arrangement of particles, however, as when precipitated from fresh water upon contact with salt water, the same clay might be slightly permeable because of numerous interstitial spaces which exceed the range of molecular attraction.

The aggregate surface-area of particles has a very important relation to the permeability of a material, being directly proportional to the frictional resistance offered to movement of percolating water. In order to indicate the relative resistance of various classes of material, the surface-area of a one-centimeter cube has been computed, subdivided first into cubes, second into spheres of equivalent volume, and third into square flakes of equivalent volume and with thickness of one-fiftieth of the cube.

Table 2--Surface-area of a one-centimeter cube variously subdivided

Class of material	Cubes		Spheres of equal volume		Square flakes of equal volume-thickness 1/50 of cube	
	Edge	Surface-area	Diameter	Surface-area	Edge	Surface-area
	mm	sq in	mm	sq in	mm	sq in
Gravel	10	0.93	12.4	0.79	70.7	93
Sand	1	9.3	1.24	7.9	7.07	sq ft 6.46
Sand	0.1	93	0.12	79	0.71	64.6
Silt	0.01	sq ft 6.46	0.012	sq ft 5.48	0.07	646
Clay	0.001	64.58	0.0012	54.8	0.007	6458
Clay	0.0001	645.8	0.00012	548	0.0007	acre 1.48

As indicated by Table 2, the aggregate surface-area of silt-particles is one thousand times greater than the original sphere or cube. If in flake form, the original is 118 times that of the original sphere, and the aggregate area of silt-particles is 118 thousand times greater than the original sphere. As colloidal clay the aggregate surface-area in flake form amounts to 1.48 acres. These data clearly illustrate the reason for the relative impermeability of silt and clay, especially where the particles are of flake form, as is the case with plastic clays.

Water-table

Definition--The water-table is defined as the upper surface of a zone of saturation except where that surface is formed by an impermeable body (O. E. Meinzer, Outline of ground-water hydrology, W.S.P. 494, U.S. Geol. Sur., 1923). It is the surface of top or shallow ground-water.

Occurrence--A water-table will form only in permeable material. Such material permits drainage, that is, movement of ground-water in response to the force of gravity. A water-table cannot exist in an impermeable material such as dense clay, even though saturated. In a slightly permeable material such as pure clay with "honeycomb" arrangement of particles, or clay with a considerable intermingling of larger particle-sizes, a somewhat indefinite water-table may exist. There are interstitial spaces in such material which exceed the range of molecular forces and in which capillarity acts but gravity only to a minor degree. Due to small permeability, an auger-hole penetrating below the water-table in such material would fill very slowly, if at all, and may give an inaccurate indication of the water-table.

Where interstitial spaces are great enough to permit gravity to act freely, a true water-table will form. Even here, if there is a large proportion of fine-grained materials giving low permeability, the movement of interstitial water is slow and a hole penetrating below the water-table may stand several hours or days before it fills to the level of the water-table. It is only in free-draining permeable materials, such as coarse silt free from clay, clean sand, or gravel, that the position of the surrounding water-table will be registered promptly and with reasonable accuracy by the water-level in a well or test-hole.

Fluctuations--Water-levels in shallow wells and test-holes usually register the elevation of water-table in the surrounding material. Exceptions occur when ground-water has not free access to the well due to the casing being sealed or surrounding material being impermeable. Surface-water discharging into the casing, either at the top or through shallow perforations, will also vitiate the record. As a general rule water-table fluctuations take place slowly, and all sudden changes in water-level should be investigated before acceptance as rise or fall of the water-table.

Fluctuations of the water-table ordinarily represent volumetric adjustment of ground-water to variations in rate of ground-water flow produced by changes either in rates of ground-water supply and draft, or by changes in permeability of the material through which the water moves. In addition, there are other causes of fluctuation not so generally recognized. The important specific causes of water-table fluctuation are herewith listed, accompanied by reference to illustrating graph where available.

(A) Change in rate of ground-water flow due to supply may result from penetration to the water-table of (1) infiltration from rainfall or melting snow (Fig. 6), (2) absorption from irrigation or surface-flooding (Fig. 6), (3) absorption from effluent

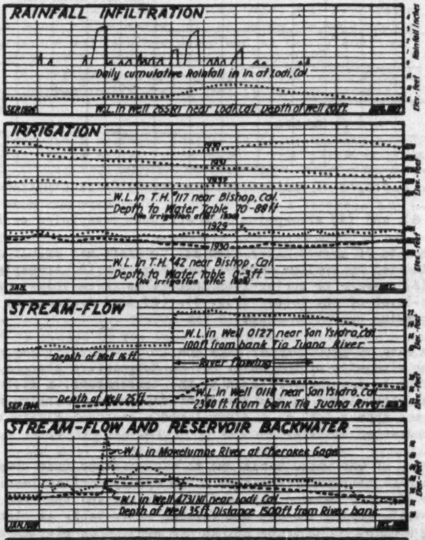

Fig. 6--Graphs of typical annual water-table fluctuations

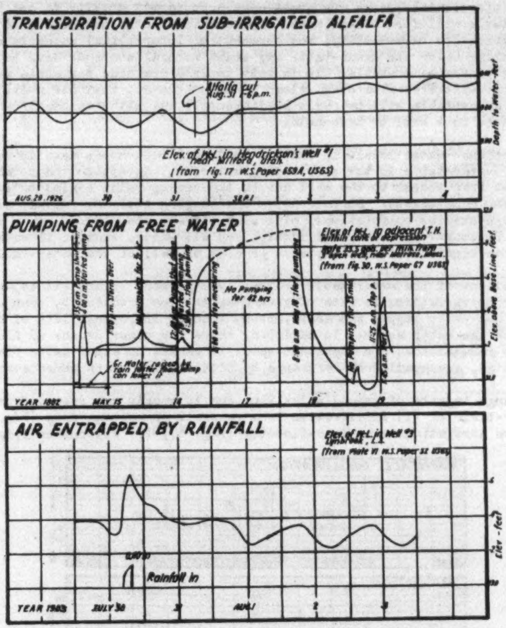

Fig. 7--Graphs of typical daily water-table fluctuations

stream-flow (Fig. 6), and (4) absorption from effluent reservoirs or lakes (Fig. 6).

(B) Change in rate of ground-water flow due to draft may result from (1) evaporation from soil moistened by shallow water-table (Fig. 6), (2) transpiration from vegetation (Fig. 7), (3) seepage or spring-flow into lakes, reservoirs, or streams controlled by surface-level of the latter (Fig. 6), (4) land drainage by means of ditches or tile, and (5) pumping operation (Figs. 7 and 10).

(C) Change in rate of ground-water flow due to permeability may result from (1) modification of the viscosity of the water due to temperature-changes in ground-water or soil. This effect is inversely related to the temperature, a rising temperature producing a drop in water-level as the result of decreased viscosity and more rapid flow. The effect may appear both as a diurnal and a seasonal fluctuation. It is most apparent near ground-water outlets.

(D) Fluctuations of the water-table due to causes other than change in ground-water flow--(1) Diurnal temperature-changes which modify surface-tension causing a cyclic interchange of water between the capillary fringe and the zone of saturation, with rising water-table during the day and falling water-table at night. (2) Heavy rainfall following drought which traps air in the soil, thus placing a sudden load upon the water-table which is absent in wells. The unbalanced pressure is equalized by a corresponding rise of water-level in shallow wells. The latter does not represent volumetric addition of water nor change in the elevation of the water-table (Fig. 7). (3) Other fluctuations not important or not recognized at the present stage of hydrologic progress.

Pressure-surface

Definitions--Earth-formations may be either homogeneous or heterogeneous. A "homogeneous formation" is defined as one composed of similar materials and similar arrangement of component particles, and has equal permeability throughout and in all directions. It may consist of particles of uniform size such as beach sand, or particles of widely diverse size such as glacial till or cloudburst debris. A "heterogeneous formation," on the other hand, is one composed of dissimilar materials and arrangement of particles, and has local differences in permeability. It may consist of interbedded gravel, sand, and clay; bedded sands and silts of differing size; or sand particles of similar size and shape with systematic dimensional arrangement which renders the material more permeable in a horizontal than in a vertical direction. Sands and gravel deposited by flowing streams are familiar examples of the latter.

Ground-water in a zone of saturation has the potential energy inherent in its position and moves generally downward under the pull of gravity. The energy consumed in frictional resistance by a vertical column of ground-water moving from one position to another is represented by the difference in elevation of the water-table between the two points.

In a perfectly homogeneous material, lost head is consumed progressively as percolating ground-water advances, and the latter is in complete equilibrium from the water-table down to the impermeable base material which supports it. Water in a well which penetrates such water to any depth will rise only to the water-table. Ground-water in such material is often described as being "free".

Ground-water percolating through a formation of heterogeneous structure, on the other hand, does not consume all lost head as it advances through the more permeable portions, including the aquifers. In a tightly cased well penetrating such an aquifer, water may stand at a level either above, at, or below the water-table. Such water is under hydrostatic pressure and is often described as being "confined". The less permeable material above it is commonly termed a "confining bed," and the aquifer a "confined aquifer". A confining bed may be impermeable, semi-permeable, or even permeable, the essential requirement being that it is less permeable than the adjacent underlying material.

If the static level in a confined aquifer is above the water-table, it is termed "normal," and if below, it is called "subnormal". The "pressure-surface" is an imaginary surface that coincides everywhere with the static level of water in a confined aquifer. It seldom coincides with the water-table. There may be several pressure-surfaces, each one representing pressure in a separate confined aquifer.

Bodies of perfectly homogeneous materials are infrequent in nature so that wells penetrating much below the water-table usually encounter water under pressure. Water-level in such wells registers the aggregate net pressure in the aquifers penetrated by the well and not the level of the water-table.

Causes of artesian pressure--The source of artesian pressure is usually excess hydraulic head. It is caused by the fact that in heterogeneous formations percolating water consumes energy at differing rates in materials of differing permeability. The rate of energy-consumption is the greatest in the least permeable materials, and the latter control the rate of movement throughout the formation. In the more permeable materials the rate of movement is slower than that required to consume the available head. Excess head accumulates in such materials in the form of hydrostatic or artesian pressure, the latter exceeding the weight of the overlying column of water and causing water in a tightly cased well to stand above the water-table. Artesian pressure accumulated in these more permeable materials is later consumed in forcing the water through the less permeable materials, and is entirely dissipated before the ground-water outlet is reached.

A secondary cause of artesian pressure exists in aquifers whose confining beds are impermeable and flexible. The weight of superimposed solid material above such an aquifer is in part transferred to the confined water and thus develops hydrostatic pressure within it. Artesian pressure from this source may in some formations be far greater than that due to hydraulic head alone.

Amount of artesian pressure--The amount of artesian pressure arising from excess head at any point in an aquifer depends upon the degree of slope and the extent and permeability of the confining beds. If the confining beds have but little slope, the artesian pressure will be small, even with impermeable confining beds. If, however, the confining beds have steep slopes and are impermeable, the artesian pressure may be relatively great, even though the extent of the beds is limited. On the other hand, steeply-inclined confining beds which are semi-permeable or leaky will dissipate the accumulating hydrostatic pressure so that artesian pressure is small.

Artesian pressures measured at the casing-head or ground-surface vary greatly, depending upon the degree of consolidation and permeability of the formation. In unconsolidated sedimentary formations with which the writer has had experience, such as alluvial slopes or valley-fill, the pressure seldom exceeds 15 pounds per square inch. In consolidated sedimentary formations, on the other hand, such as sandstone or cavernous limestone, much greater pressures are encountered. It is reported that in the early days of artesian-well development in the Dakotas pressures of 200 pounds per square inch were obtained in wells penetrating the Dakota sandstone (O. E. Meinzer and H. A. Hard, The artesian water-supply of the Dakota sandstone in North Dakota, with special reference to the Edgeby Quadrangle, W.S.P. 520-E, U.S. Geol. Sur., 1925). Although this is relatively high, yet average pressure in consolidated sedimentary formation frequently reaches 150 pounds.

Artesian pressure is usually thought of as having its origin in a distant "fountain-head" consisting of a free water-table in permeable material at the upper margin of the confining beds. Experience shows that pressures obtained in capped artesian wells seldom correspond with the available head. The writer offers the following explanation of this phenomenon. Heterogeneous formations are usually re-worked stream-deposits interbedded with lake or marine deposits in the lower or marginal areas. The original stream-deposits are ordinarily homogeneous, consisting of cloudburst or flood-flow debris, or glacial till. The re-working is done by under-loaded or clear-water flow, which picks up and carries away the fines, leaving the clean coarse materials along channels or at points of discharge into still water where they are spread by shore-currents. Such deposits of coarse material are later buried beneath fresh debris or till, or covered by clay beds deposited from bodies of standing water. Stream-channels on alluvial slopes and even in river-valleys are unstable, shifting from side to side with much crossing and re-crossing. As a consequence, in the process of upbuilding of alluvial slopes or valley-fills, clear water-channels become choked at the head and cut up into short segments by flood-water debris consisting of a mixture of both fine and coarse. The final result of this process is a matrix of unassorted semi-permeable or impermeable cloudburst- and flood-debris merging into impermeable lake-bed or marine clays, and interspersed or interbedded with relatively elongated but disconnected bodies of permeable sand and gravel which form the aquifers. The latter are relatively short and seldom extend back up the slope far enough to have direct connection with free water and a water-table. Artesian pressure in a well penetrating such an aquifer is derived from the local head within the aquifer, and at any point does not exceed the head created by the slope of the upper confining beds minus losses due to leakage and to percolation within the aquifer. The general absence of high artesian pressures in alluvial and lacustrine formations tends to substantiate this explanation.

Fluctuations--Water-level in wells which penetrate confined aquifers record the elevation of the pressure-surface in these aquifers. Exceptions occur if ground-water has not free entrance and exit to the casing. In contrast to water-table fluctuations, changes in elevation of the pressure-surface take place rapidly, that is, they can be measured in terms of seconds, minutes, and hours, instead of days, weeks, and months.

Fluctuations of the pressure-surface represent changes in hydrostatic pressure of confined water. These changes are produced by changes in the load supported by the water. The character of the loading upon a confined water-body is controlled by the formation. The commonly recognized types of fluctuation are produced as described below and illustrated by graphs where available.

(A) With rigid confining beds completely enclosing the aquifer, the loading can be changed by the following: (1) Change in length of water-column in a well resulting

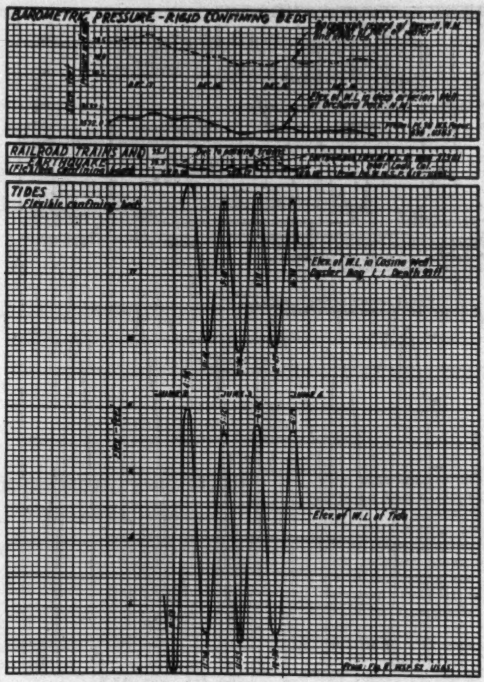

Fig. 8a--Graphs of typical daily pressure-surface fluctuations

from pumping operations, by control of artesian flow, or from casing-leakage (Fig. 8b); (2) barometric-pressure changes acting through the water-column in a well or spring (Fig. 8a); (3) depletion of the supply by overpumping to the extent of draining the voids in the upper portion of the aquifer and creating a water-table within the aquifer (slow action, Fig. 9); and (4) change in elevation of the water-table of overlying free water, provided the confining beds are semi-permeable or permeable (slow action).

(B) With confining beds which completely enclose the aquifer but have flexibility, the loading may, in addition, be affected by live loading upon the ground-surface such as: (1) Railroad trains (Fig. 8a); (2) earthquakes (Fig. 8a); (3) tides (Fig. 8a); (4) floods; and (5) barometric-pressure change acting indirectly through deflection of the flexible confining beds and partially offsetting direct action through the well.

(C) If in either of the above cases the confining beds are broken so that there is direct connection with free water, the pressure in the confined aquifer may also be affected by fluctuations of the water-table over the area of discontinuity. This will be especially noticeable if the latter is an intake area (slow action, Fig. 8b).

Pumping fluctuations

Modern deep-well development has introduced a new element into the interpretation

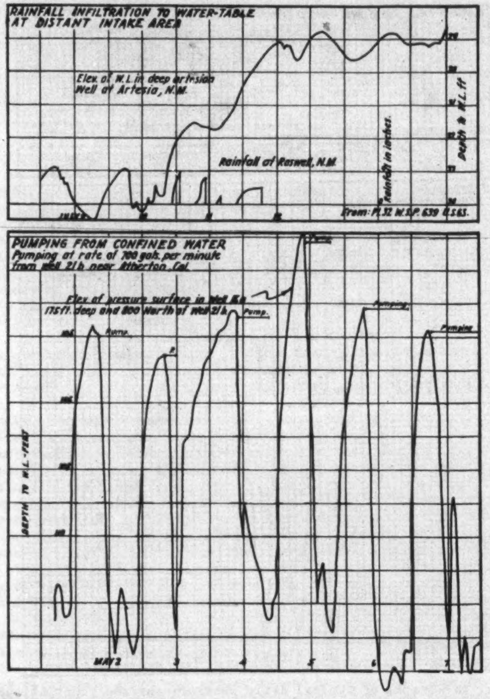

Fig. 8b--Graphs of typical daily pressure-surface fluctuations

of water-level fluctuations in wells. Pumping from a shallow well in free water, in addition to diverting a portion of the subsurface flow, produces a slowly forming cone of depression in the local water-table as water drains from the voids above the new position of the water-table. The latter is established by frictional resistance to the rapid movement of water toward the well as induced by the pump. Pumping from a deep well penetrating confined water, on the other hand, will produce a cone of depression not in the water-table but in the pressure-surface of a buried aquifer. This cone may include the whole area of the aquifer, extending rapidly to a distance of a mile or more from the well and producing a drop of water-level in all wells which penetrate the aquifer. Such a cone of depression, although it represents frictional resistance to the rapid movement of water toward the well as induced by the pump, does not immediately represent the voiding of any water-bearing material. Water extracted from such a well is primarily diverted from the subsurface flow, but in time may include that squeezed from the aquifer by the added weight of overlying solid material. If the overlying confining beds are semi-permeable or permeable, it may in time also represent water slowly drained from the zone of free water above the aquifer. In the latter case the water-table will drop more or less uniformly throughout the area embraced by the cone of pressure-depression, progressively reaching a stage of equilibrium from the margin inward as it attains the new level of the pressure-surface (Fig. 10). If the confining beds are impervious, however, there may be no water derived

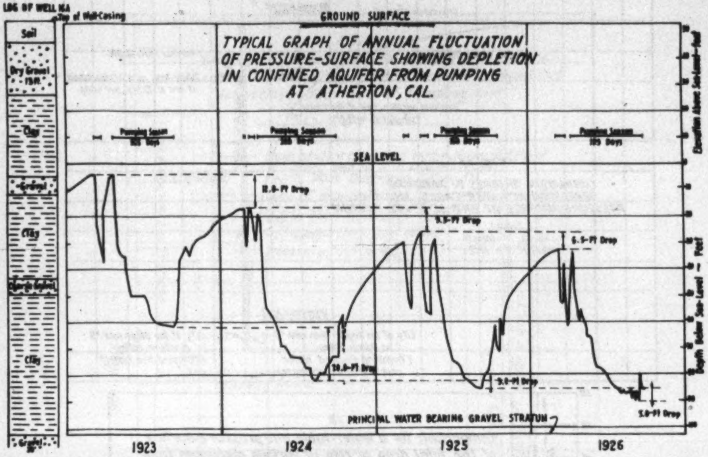

Fig. 9

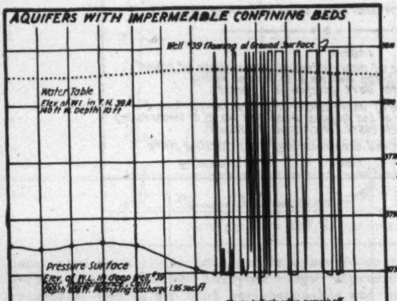

Fig. 10--Comparison of water-level in adjacent wells registering pressure-surface and water-table over confined aquifers penetrated by pumped wells (these are adjacent record wells and show effect pumped wells in vicinity)

from this source nor any appreciable drop in the water-table (Fig. 10).

Two 72-hour pump-tests made by the writer illustrate the difference between cones of depression of the water-table and the pressure-surface. City of San Diego Well No. 9 in Mission Valley was a field-perforated 12-inch cased well 90 feet deep. It penetrated a permeable valley-fill formation which was logged by the driller as sand 45 feet, sand and gravel 15 feet, gravelly clay 3 feet, gravel 5 feet, and cemented sand (impermeable) 22 feet. Water in this formation was free, with a water-table 7 feet below the surface. The well had a pumping capacity of 1.0 second-feet, and when pumped a cone of depression was formed in the adjacent water-table. The drawdown in the well at the end of two hours' pumping was 18.5 feet, which remained constant throughout the 72-hour test. The radius of the cone of depression was 310 feet at the end of 24 hours, and 340 feet at the end of 72 hours.

City of Los Angeles Deep Well No. 15 in Owens Valley is a field-perforated 12-inch cased flowing artesian well 265 feet deep. It

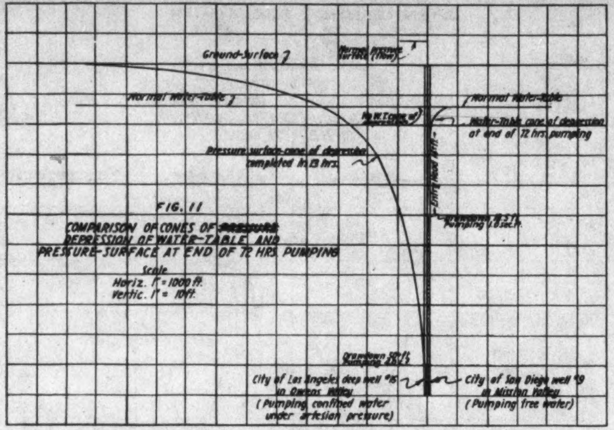
Ground-Surface
Normal pressure surface (flow)
Normal Water-table
Normal Water-table
No W.T. cone of depression
Water-Table cone of depression at end of 72 hrs. pumping
Pressure surface-cone of depression completed in 13 hrs.
Drawdown 18.5 ft. Pumping 1.0 sec.ft.
Drawdown 50+ft. Pumping 4.0 s.f.
City of Los Angeles deep well #15 in Owens Valley (Pumping confined water under artesian pressure)
City of San Diego well #9 in Mission Valley (Pumping free water)

FIG. 11

COMPARISON OF CONES OF ~~PRESSURE~~ DEPRESSION OF WATER-TABLE AND PRESSURE-SURFACE AT END OF 72 HRS. PUMPING

Scale
Horiz. 1" = 1000 ft.
Vertic. 1" = 10 ft.

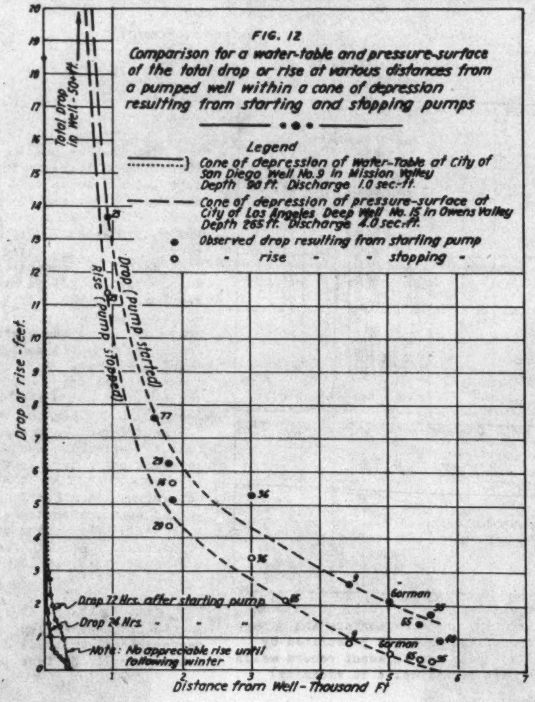

FIG. 12

Comparison for a water-table and pressure-surface of the total drop or rise at various distances from a pumped well within a cone of depression resulting from starting and stopping pumps

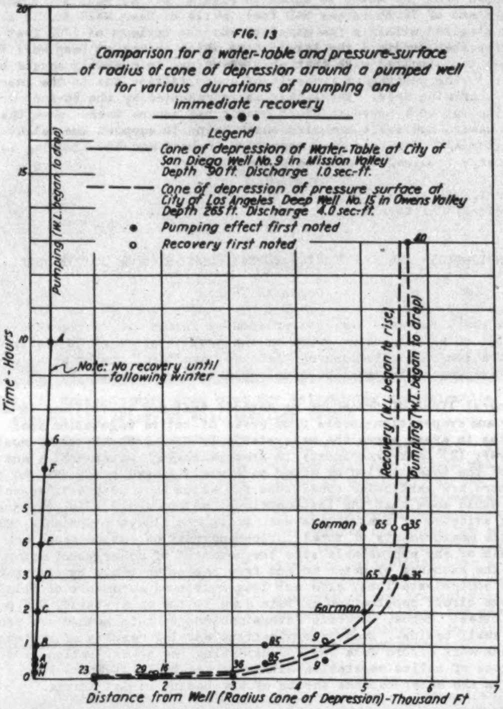

FIG. 13

Comparison for a water-table and pressure-surface of radius of cone of depression around a pumped well for various durations of pumping and immediate recovery

penetrates an alluvial cone and lake-bed formation composed of interbedded sand, gravel, and impermeable lake-bed clay. Approximately 35 per cent of the formation is permeable, and 65 per cent semi-permeable and impermeable. There is a shallow zone of free water, the depth to water-table averaging 7 feet below the surface. All water-bearing strata with which the well is connected contain confined water under pressure. The well had a pumping capacity of 4.0 second-feet when tested, and when pumped a cone of pressure-depression was formed which was registered by an almost instantaneous drop in adjacent wells. The instantaneous drawdown in the well slightly exceeded 50 feet and remained constant throughout the test. The radius of the cone of pressure-depression was 5700 feet at the end of 13 hours, and did not increase thereafter. The maximum radius of the cones of pressure-depression of five similar wells which were tested in the same formation varied from 5000 to 7000 feet, and was attained within from 13 to 24 hours after pumping commenced.

A graphical comparison of the cones of depression surrounding the wells is shown upon Figure 11. The total drop at various distances from each well is indicated on Figure 12. The water-table surrounding Well No. 9 dropped progressively during the test, although it was proceeding at a much reduced rate at the end of the 72-hour period when drainage of voids was almost complete. The drop of the pressure-surface surrounding Deep Well No. 15 was instantaneous when it occurred and did not change during the test. The time required for the radius of the cone of depression to attain various distances from the wells is shown on Figure 13. At Well No. 9 the maximum distance at the end of 72 hours was 340 feet, while at Deep Well No. 15 a distance of 3000 feet was attained within a few minutes, and the maximum of 5700 feet in 13 hours. The smaller rise than drop and the lag in time which occurs at Deep Well No. 15 when pumping stopped, as compared with that when starting, is probably caused by shrinkage of the aquifer during pumping as a result of consolidation due to the increased weight upon flexible confining beds. The latter is represented by the 50-foot drawdown at the well, equivalent to a pressure of 22 pounds per square inch. When the pump is at rest, this is upward hydraulic pressure which helps to support the weight of the overlying solid material. The temporary reduction in head and the time-lag is an expression of the energy required to reinflate the aquifer.

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TRANSPIRATION- AND EVAPORATION-LOSSES FROM AREAS OF NATIVE VEGETATION

Colin A. Taylor

In recent years the need for greater economy in the use of the water-resources of the West has led to an increasing study of the problem of water-losses by transpiration and evaporation. In establishing the most beneficial use of water within a basin, the use by native vegetation must be considered and evaluated.

Three general lines of procedure or methods that may be followed in determining transpiration- and evaporation-losses from areas of native vegetation are: (1) Soil-moisture studies in areas where the water-table is beyond the reach of roots of the vegetative cover; (2) tank-experiments in areas with high water-table; and (3) measurements of the total inflow of water to a small closed basin and the outflow from the basin. There are particular conditions for which each method is especially adapted and, while it would seem that the last-mentioned method would offer the most desirable and convincing evidence of consumptive use, it is not always practical. Closed basins, wherein accurate measurements of total inflow and outflow can be made, are not numerous. In a basin of any appreciable size the movement of underground water is difficult to evaluate. The exchange of water to and from the water-table by living streams, underflow past control-stations, slow but long-continued movements of film-moisture resulting from the direct penetration of rain down to the water-table, and other items, cause uncertainties. Hence, accurate determinations by this method are usually limited to relatively small basins. Such determinations and the results of soil-moisture studies and tank-work afford data for approximating the transpiration- and evaporation-losses from areas of native vegetation within larger basins. These losses are important items in the water-balance sheets of the basins in California.

Soil-moisture methods find their principal application on well-drained slopes where the water-table is not reached by the roots of the vegetative cover. In southern California native vegetation still covers large areas on the fans and steeper slopes adjacent to the mountains. The water-table is generally far below the ground-surface on the higher fans--400 to 600 feet in many cases.

Figure 1 shows the cover on the area east of Cucamonga Creek north of Upland, California. Much of this area is so rocky that dug pits must be used in following the depth of rainfall-penetration and for obtaining soil-samples. Occasionally small plots can be found where soil-tubes can be used to 18-foot depths. Records have been continued on the area shown in Figure 1 since the publication of the bulletin "Rainfall penetration and consumptive use of water in Santa Ana River Valley and Coastal Plain in 1930" (Bull. No. 33, State of California, Dept. Public Works, by H. F. Blaney, C. A. Taylor, and A. A. Young). The methods used in determining the transpiration- and evaporation-losses are as outlined in Chapter 11 of this bulletin. Table 1 lists the records for the seasons of 1931-32 and 1932-33. Up to February 2, 1932, the seasonal rain for 1931-32 amounted to 18.70 inches including a storm of 3.79 inches ending February 2, 1932. Samples taken within 24 hours after the rain stopped showed a penetration of 9 feet but with sufficient moisture present to wet a 16-foot column to the moisture-equivalent after allowing for normal downward drainage. Between February 7 and 19, 9.18 inches of rain fell, causing 5 inches of water to penetrate

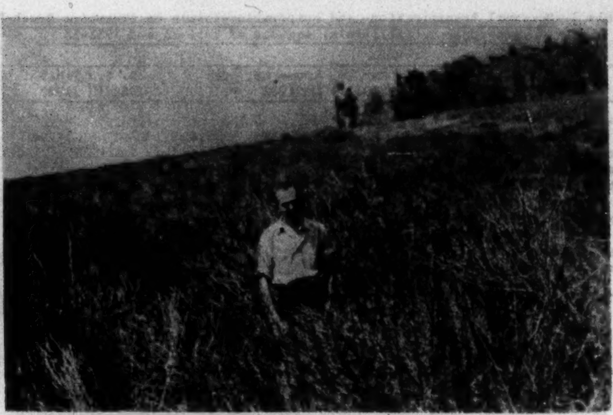

Fig. 1 Brush-covered area used for determining transpiration- and evaporation-losses by soil-sampling method

below the 16-foot level. All of the remainder of the rain for 1931-32 was held above the depth of sampling. In the 1932-33 season there were only 15.40 inches of rain and none of it penetrated below a depth of 9 feet. The results for these two seasons are in line with the conclusion set forth in Bulletin 33, State of California, that a seasonal rainfall of less than 19 inches is usually consumed by evaporation and transpiration in brush-covered areas before the ground-water receives any increment by direct downward penetration of rain.

As long as there is a dry subsoil, the determination of transpiration and evaporation by soil-sampling methods is relatively simple. When there is no dry subsoil and moisture is draining downward below the depth of sampling for an interval following each storm, the labor of obtaining sufficient soil-samples is enormously greater.

When the roots of the vegetative cover extend to the water-table, it is not possible to determine the total transpiration and evaporation by soil-sampling and recourse must be had to tank-work. The principal application for tank-studies is in areas of high water-tables such as shown in Figure 2. Here the tanks containing Bermuda grass are set in a field of the same grass replicating natural conditions as closely as possible. This is perhaps the most important item to consider in tank-work--that of securing a normal exposure for the growth in the tanks. If the data are to be used in estimating

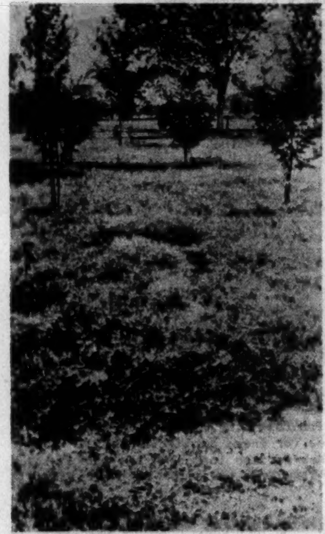

Fig. 2--Transpiration and evaporation from areas with high water-table by plants grown in natural environment (tanks with Bermuda grass are in center of picture)

Table 1--Seasonal transpiration- and evaporation-losses on Cucamonga Brush-Plot near Upland, California, seasons of 1931-32 and 1932-33

Item	Feb. 3, 1932	Mar. 29, 1932	June 25, 1932	Sep. 2, 1932	Nov. 3, 1932	Feb. 11, 1933	Nov. 27, 1933
Total seasonal rain to date in inches......	18.70	29.03	29.37	29.37	29.37	14.08	15.40
Depth of penetration in feet.............	9	>18	.....	.....	.....	9	.....
Rain stored in soil 0-16 feet in inches.	11.66	11.53	3.88	0.59	0.00	9.26	0.00
Penetration below 16-foot level in inches	0.00	5.00	5.00	5.00	5.00	0.00	0.00
Seasonal evapo-transpiration to date in inches......	7.04	12.50	20.49	23.78	24.37	4.82	15.40

Table 2--Transpiration and evaporation from tanks of Bermuda grass at San Bernardino, California, June, 1929 to April, 1932

Year	Month												Total
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch
Average for tanks with water-table at 2-foot depth													
1929	....	....	....	....	....	5.60	6.51	6.23	3.56	2.89	1.52	0.93	
1930	0.45	0.71	1.05	2.72	2.71	5.39	6.42	5.34	3.44	....	....	....	
1931	....	....	1.86	2.58	3.38	4.54	7.06	5.08	3.42	2.33	2.47	1.96	
1932	1.56	....	....	....	....	....	....	....	....	....	....	....	
Means	1.00	0.71	1.46	2.65	3.04	5.18	6.66	5.55	3.47	2.61	2.00	1.44	35.77
Average for tanks with water-table at 3-foot depth													
1929	....	....	....	....	....	5.22	5.49	5.34	2.90	2.77	1.38	0.74	
1930	0.77	0.66	1.01	1.97	2.10	4.54	5.44	3.90	3.08	....	....	....	
1931	....	....	....	2.33	2.36	3.38	5.58	4.37	2.56	1.84	2.33	1.32	
1932	1.13	....	....	....	....	....	....	....	....	....	....	....	
Means	0.95	0.66	1.01	2.15	2.23	4.38	5.50	4.54	2.85	2.30	1.86	1.03	29.46

losses from field-areas, the tanks must be set in a field of growth similar to that in the tank and the outside growth must completely surround the tank. The height of the growth inside and outside must be approximately the same and there must be no overhang beyond the area of the tank. If these conditions are not met, uncertain and often extreme conversion or reduction-factors must be applied.

Table 2 is made up from data in Chapter 11 of State of California Bulletin No. 44. For the period June 1929 to April 1931, inclusive, the losses reported are the draft on the water-table only and do not include the evaporation after rain-storms. It is estimated that the inclusion of surface evaporation following rains would raise the average annual total loss approximately two inches for these particular tanks. This would make an average seasonal total of 37.8 inches for the loss from the tanks with the two-foot water-table and 31.5 inches for the loss from the tanks with the three-foot water-table.

When the water-table is at or close to the ground-surface, the swamp type of vegetation appears which consumes large quantities of water. Measurements of losses from this type of vegetation were made by the use of tanks set in a swamp adjacent to the Mojave River near Victorville, California. A general view of the station is shown in Figure 3 and the location of the tanks in the swamp indicated in Figure 4. The

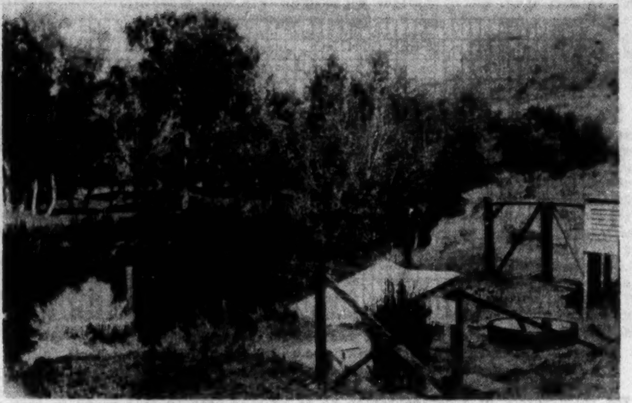

Fig. 3--Victorville station where demonstration was made of the effect of exposure on results from tank-work

Fig. 4--Replicating natural conditions in determining transpiration and evaporation from tule swamp-area by use of tanks (rod is resting on edge of 6-foot tank)

mean annual evaporation- and transpiration-use of water from a six-foot tank of tules in the swamp was 78.45 inches.

In order to demonstrate the effect of exposure on tank-work, a two-foot tank of tules was set in the ground away from the tule-swamp. The growth in this isolated tank consumed the equivalent depth of over 272 inches per year or nearly 3.5 times as much water as the growth with the normal exposure in the six-foot tank located in the swamp. This record indicates the impracticability of applying to field-conditions the records of tests made in isolated tanks wherein the plants are grown away from their natural environment.

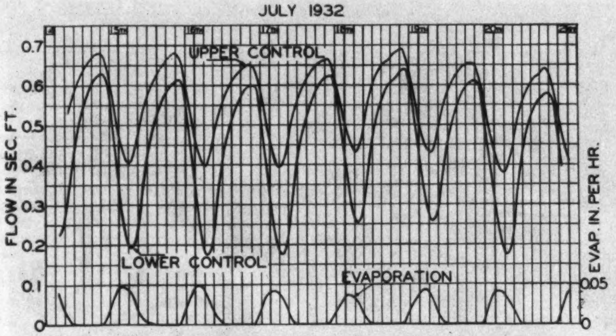

Fig. 5--Flow of water past two bed-rock controls near San Bernardino, California, and the rate of evaporation from a shallow black-pan evaporimeter

The third method of experimentation to be touched upon in this paper is that of measuring the inflow and outflow to small closed basins or sections of stream-channel. By measuring the inflow to and outflow from 12.8 acres of moist-land growth on Temescal Creek near Corona, California, it was found that the loss by transpiration and evaporation amounted to 12.9 acre-inches per acre for the 30-day period from April 28 to May 27, 1929 (Bull. No. 33, State of California, Chap. IV).

In 1931 and 1932 similar measurements were made on Coldwater Canyon near San Bernardino, California. In 1932 a gaging-station called the "Upper control" was located 7965 feet upstream from the gaging-station called the "Lower control". Both stations were on bed-rock and the area of the canyon bottom fill was 8.25 acres and it varied in width from 15 to 80 feet. The record of flow past the two controls from July 15 to 20 is shown in Figure 5. For these six days the average loss per day between the two controls was at the rate of 0.32 inch depth or acre-inch per acre of canyon bottom fill. For the same period the average loss from the shallow black-pan evaporimeter at Pomona was at the rate of 0.33 inch per day. The highest rate of loss occurred on September 8, 1932, when there was a measured loss of 0.52 acre-inch per acre of canyon bottom fill between these two controls and an evaporation of 0.50 inch from the evaporimeter near the mouth of the canyon. On this day there was a hot wind blowing down the canyon and the maximum temperature was 111° in a standard Weather Bureau shelter located near the mouth of the canyon.

The indicated loss for the six-month growing season from May to October, inclusive, 1932, was at the rate of 53.85 acre-inches per acre of canyon bottom fill. For this same period the shallow black-pan evaporimeter lost 47.78 inches, which is 6.07 inches less than the loss from moist area.

Rain interferes with measurements of this type so that records were not obtained from November to April. This is the dormant season for most of the vegetation in the canyon bottom and nearly all of the trees drop their leaves.

In 1932 the total loss from the evaporimeter was 71.77 inches. If 6.07 inches be added to this value for the increase in summertime use over the loss from the evaporimeter, a total of 77.84 inches is obtained. This is most probably high because the transpiration and evaporation during the dormant season are undoubtedly less than the loss from the evaporimeter. However, the value 77.84 inches for the annual use is not greatly different from the mean annual loss of 78.45 inches from the six-foot tule-tank at Victorville.

From the foregoing it is indicated that in southern California loss of water by transpiration and evaporation from areas of native vegetation may range from as low as one acre-foot per acre per year or less to as high as 6 1/2 acre-feet per acre per year. The lower value applies to areas dependent entirely on rainfall and the higher value to moist areas with the water-table at or close to the surface throughout the year. The average losses from large areas may be expected to fall within this range depending on the distribution of the type of growth, and an estimation may be made with the aid of a map classifying the type of cover.

Troxell (Bull. No. 44, State of California, Dept. Public Works, Division Water Resources, Water-losses under natural conditions from wet areas in southern California, 1933: Part 1--Report of a cooperative investigation by the Division of Irrigation, Bureau of Agricultural Engineering, U. S. Department of Agriculture; Part 2--Report of a cooperative investigation by the Water Resources Branch, Geological Survey, U. S. Department of the Interior) has studied the ground-water supply and natural losses in the valley of the Santa Ana River between the Riverside Narrows and the Orange County line. In this work the area was mapped and the bottom land classified according to the type of cover. A record is given of the non-economic loss of water from 4040 acres along the Santa Ana River from Riverside Narrows to Prado, and an estimate is made of the inflow to the River from ground-water above Lower Santa Ana Canyon. For the period October 1930 to September 1932, the mean annual loss of water by transpiration and evaporation was estimated to be 50 inches for the moist land bordering the River.

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DISCUSSION OF "TRANSPIRATION- AND EVAPORATION-LOSSES FROM AREAS OF NATIVE VEGETATION"

O. V. P. Stout

Experiments made in the Sacramento-San Joaquin Delta on consumptive use of water by aquatic growths have yielded results that are not inconsistent with those reported by Mr. Taylor from his experiments in southern California. The delta experiments included also non-crop growths not strictly aquatic, although some of them may be designated as water-loving plants.

The tank-method was used in the determinations, the conditions being those described by Mr. Taylor as calling for this method. The soil-surface in 15,000 tanks would amount to one acre.

In the latter part of June 1929, cat-tails and tules were dug up in Reclamation District No. 999, near Clarksburg, about 16 miles below Sacramento, on Sacramento River, and transplanted to 12 tanks in a situation nearby where there was nearly complete exposure to Sun and wind. Cat-tails were set in six of them and tules in six. A tractor ran over one of the cat-tail tanks in October and it was not used thereafter. Record of use of water was begun on July 15, and continued through the seasons of 1929, 1930, and 1931. The results for 1930, the complete year of record, are submitted in Tables 1 and 2.

Notwithstanding the astonishingly large amount of water used, the plants in the tanks were somewhat smaller and less robust in appearance than those growing at large in the same vicinity. It was realized that the observed use of water under such conditions of exposure was not representative of plants in dense patches. Four tanks, therefore, two of tules and two of cat-tails, were set in the midst of a patch on King Island, northwest of Stockton, and four others, all tules, in a patch on Simmons Island, in Suisun Bay.

A complete year of record was obtained at King Island in 1932, with results as set forth in Table 3.

Table 1--Use of water by cat-tails grown in tanks, near Clarksburg, Reclamation District 999, 1930

Tank number	Use of water in acre-feet per acre												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
2	0.43	0.19	0.52	1.32	2.04	2.09	2.48	2.64	1.87	1.54	0.69	0.39	16.20
3	0.40	0.17	0.44	1.08	1.95	2.29	2.32	2.21	1.55	1.36	0.66	0.35	14.78
4	0.42	0.17	0.52	1.41	2.43	2.74	2.86	2.70	1.65	1.52	0.67	0.36	17.45
5	0.42	0.16	0.52	1.34	2.25	2.37	2.34	1.93	1.17	0.91	0.44	0.31	14.16
6	0.40	0.17	0.60	1.64	2.46	2.94	3.53	3.31	2.16	1.74	0.73	0.40	20.08
Means	0.41	0.17	0.52	1.36	2.23	2.49	2.71	2.56	1.68	1.41	0.64	0.36	16.53

Table 2--Use of water by tules grown in tanks, near Clarksburg, Reclamation District 999, 1930

Tank number	Use of water in acre-feet per acre												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
7	0.42	0.18	1.01	2.16	3.10	3.82	5.08	4.33	2.65	2.14	0.87	0.41	26.17
8	0.42	0.17	0.63	1.61	2.25	2.56	3.33	2.88	1.88	1.62	0.72	0.33	18.40
9	0.43	0.19	0.73	1.53	1.93	2.24	3.22	2.71	1.74	1.49	0.65	0.34	17.20
10	0.40	0.17	0.77	1.53	2.01	2.65	3.27	2.72	1.90	1.56	0.70	0.35	18.03
11	0.43	0.17	0.56	1.46	1.86	2.02	2.55	2.46	1.55	1.58	0.71	0.40	15.75
12	0.42	0.17	0.54	1.22	1.90	2.37	2.52	2.36	1.50	1.35	0.62	0.34	15.31
Means	0.42	0.18	0.71	1.58	2.18	2.61	3.33	2.91	1.87	1.62	0.71	0.36	18.48

Table 3--Monthly use of water by cat-tails and tules grown in tanks at Camp 3, King Island, 1932*

Tank number	Plant	Water-surface above ground-surface	Use of water in acre-feet per acre												Year
			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
		feet													
1	Cat-tails	0.0	0.08	0.10	0.43	0.48	0.58	0.99	0.75	0.27	0.29	0.30	0.19	0.10	4.56
2	Cat-tails	1.0	0.17	0.27	0.49	0.50	1.02	0.95	1.35	0.93	0.72	0.57	0.35	0.18	7.50
3	Tules	1.0	0.10	0.20	0.55	0.83	1.50	1.20	1.36	0.91	0.75	0.80	0.35	0.08	8.63
4	Tules	0.0	0.14	0.15	0.33	0.56	0.89	0.59	0.53	0.26	0.27	0.20	0.08	0.05	4.05

*Plants grown from the roots of the original transplanting in the summer of 1930. On February 11, 1932, there were no live or green stalks of plants in any of the tanks or in the patch, so there must have been no transpiration. By March 9 there were green stalks from one to two feet high above the ground-surface in the tanks. On March 19 the patch was burned over by the farmer, and the next day the upper parts of the live stalks in the tanks were cut off. The water was pumped out of the tanks about the middle of April, and fresh water put in. As the season advanced it was noted that cat-tails in Tank No. 1 were undersize as compared with adjacent plants in the patch. Crowding of roots in the soil of the tank is believed to account for the backward growth. The tules in Tank No. 4 were blown down in June and, although restored to upright position, they did not thrive thereafter. Cat-tails in Tank No. 2 and tules in Tank No. 3 seemed normal as compared with plants in the patch. There were some green stalks in the tanks until they were killed by freezing in mid-December.

The consumptive use of water from the King Island tanks in 1933 was of about the same order of magnitude as in 1932.

The best record at Simmons Island was obtained in 1932, after the original transplanting had been replaced by a new set of plants. The record is not so precise as at King Island, for it was not practicable to set the tanks high enough to preclude overflow by the highest tides. This deranged the record and made some interpolation necessary. The results for 1932 at Simmons Island are shown in Table 4.

Table 4--Monthly use of water by tules grown in tanks on Simmons Island, near Port Chicago (Bay Point), 1932

Tank number	Water-surface above ground surface	Use of water in acre-feet per acre								May 7-Dec. 31
		May 7-31	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
	feet									
1	0.0	0.51	0.67	0.91	0.96	0.87	0.67	0.47	0.13	5.19
2	1.0	0.75	0.98	1.03	0.77	0.52	0.47	0.48	0.11	5.11
3	1.0	0.41	0.48	0.72	0.80	0.63	0.56	0.54	0.09	4.23
4	0.0	0.62	0.59	0.82	0.70	0.51	0.61	0.45	0.11	4.41

It is presumed that the greater expanse of water and the salt-content of the water at Simmons Island may account for most of the difference in use of water by tules there and at King Island.

For the purposes of the studies made by the Division of Water Resources of the State of California it has been estimated that the use of water by tules, cat-tails, and similar aquatic growths in the Sacramento-San Joaquin Delta amounted in 1929 to 9.63 acre-feet per acre (State of California, Dept. Public Works Bull. No. 27, p. 69). This figure is somewhat in excess of the indications at King Island, where the conditions are most nearly representative of a large proportion of the tule-acreage. It may be considered as taking into account the large aggregate acreage disposed in fringes along channels and bodies of water, and otherwise exposed to conditions approximating those under which the astonishingly heavy use of water was found in the Clarksburg experiments.

Tables 5 to 8 set forth results obtained in 1932 from 20 tanks set in a plot of peat-ground on King Island, about 15 miles northwest of Stockton. The plot bore a crop of popcorn so that in the height of the season of growth the exposure of the tank weeds to wind and Sun was somewhat less than that to which plants growing at large were subjected. The usual method of transplanting was to remove from the field a cylinder of earth(peat) bearing a good stand of seedling plants, and set it in the tanks. This procedure usually gives better than a field-stand in the tanks, and in such case it is fair to assume that tank-use of water, in acre-feet per acre, is correspondingly greater than field-use.

In experiments with the King Island weed-tanks in 1933, Western Golden Rod in two tanks used 5.68 and 7.97 acre-feet per acre in the period May 27 to November 10. Dock, from early spring to November 8, used 10.23 and 10.58 acre-feet per acre, respectively, in the two tanks that were run through the season. The five tanks of so-called kelp (*Polygonum amphibium* var. Hartwrightii), grown from roots set in November 1932, used in the full year to November 1933, 7.21, 6.04, 8.72, 4.90, and 6.21 acre-feet per acre, respectively. Lamb's quarters, from early May to September 20, in five tanks, used from 3.85 to 4.58 acre-feet per acre.

Mixed volunteer growths of weeds were observed from the time of sprouting in six tanks, about July 1, until November 8. The growths included cocklebur, watergrass, wild radish, volunteer barley, smartweed, lamb's quarters, pigweed, nut grass, Johnson grass, and one cat-tail. Use of water ranged from 2.45 to 3.59 acre-feet per acre.

The tanks in 1933 were not sheltered except by a barley field surrounding the plot in early season and some growth of weeds in the plot fence in later season.

Table 5--Use of water by smartweed grown in tanks at King Island, 1932

Tank number	Depth to water-table	Water used	Yield
	feet	acre-ft/acre	tons/acre
2	2.5	10.04	19.90
6	3.5	9.48	18.01
10	3.0	8.49	18.59
14	2.0	9.84	23.62
18	1.5	10.65	20.52
Means..........................		9.70	20.13

Table 6--Use of water by prickly lettuce grown in tanks at King Island, 1932

Tank number	Depth to water-table	Water used	Yield
	feet	acre-ft/acre	tons/acre
3	2.5	5.87	7.30
7	3.0	6.00	8.66
11	2.0	4.61	6.07
15	1.5	3.60	4.45
20	3.5	8.31	12.88
Means..........................		5.68	7.87

Table 7--Use of water by cockleburs grown in tanks at King Island, 1932

Tank number	Depth to water-table	Water used	Yield
	feet	acre-ft/acre	tons/acre
4	1.5	7.24	7.98
8	3.5	5.21	8.16
12	3.0	4.82	5.72
16	2.5	5.21	6.57
19	2.0	4.61	4.98
Means..........................		5.42	6.68

Table 8--Use of water by nettles grown in tanks at King Island, 1932

Tank number	Water used	Yield	Remarks
	acre-ft/acre	tons/acre	
1	5.67	8.24	The nettle in Tank 1 was grown from root; plants in other tanks were seedlings
5	4.00	1.88	
9	5.15	2.55	
13	4.14	1.97	
17	5.92	2.59	Tank 17 supported also a horseweed which yielded at the rate of 1.43 tons per acre
Means, Tanks 5,9,13	4.43	2.13	

A count of tule-stalks on small areas in the patch at King Island indicated an average density of about 750,000 stalks to the acre. The corresponding density in a tank is 50 stalks. The tanks have, in general, contained close approximations to this number, so that conditions in that respect were representative.

An apparently heavy growth of smartweed on a small patch yielded at the rate of 4.3 tons of air-dry weeds to the acre--only a minor fraction of the rate of yield in tanks.

Small patches of prickly lettuce, disposed, by a partial plowing, in a heavy stand in rows about three feet apart, yielded at a rate about equal to the minimum found in the tank-experiments.

It is submitted that the record of experiments with weeds indicated that the general run of them in the region of the experiments uses, in proportion to the ground actually occupied, more water than does the general run of crop-plants. Conditions in many irrigated regions--notably the Sacramento-San Joaquin Delta--are especially favorable to propagation and growth of weeds. Saving of water is in such case a material incentive in the battle against weeds.

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FUNDAMENTAL PRINCIPLES GOVERNING THE CONTROL OF GROUND-WATER

Willard Gardner, T. R. Collier, and Doris Farr

(Abstract of proposed bulletin to be published by Utah Agricultural Experiment Station; contribution from Department of Physics of the Experiment Station, publication authorized by Director, May 31, 1934)

As was pointed out originally by Slichter, the generalization of Darcy's law is nothing more nor less than the criterion for the existence of a velocity-potential for the macroscopic velocity of moisture in the soil. If the velocity is eliminated from the equation of continuity for an incompressible fluid by means of the generalized Darcy equation, it leads immediately to Laplace's equation. It is evident, therefore, that if this law is to be relied upon any rational solution of problems in drainage and well-construction must be based primarily upon this equation or the equations from which it is derived.

An attempt is made in the discussion to make application of this procedure to the solution of certain practical problems.

(1) The simplest case is uniform one-dimensional flow where water moves in one direction through a uniform stratum of uniform thickness. The potential gradient is constant in this case and the pressure-gradient may vanish. If it does not vanish, it will be uniform, that is, it will not differ from point to point.

(2) If the water-bearing material is bounded by plane faces, the distance apart of these faces decreasing in the direction of flow, the velocity will increase in the direction of flow and the potential gradient also in proportion. The velocity-potential $k\Phi$ is made up of two terms

$$k\Phi = k(\varphi + p/\rho)$$

where k is the transmission-constant characterizing the porous substance and the fluid, φ is the gravitational potential, p is the hydrostatic pressure, and ρ is the density. By choosing an arbitrary horizontal datum-plane, this potential may be written

$$k\Phi = khg$$

where h measures the height above the datum-plane to which water would rise in a tube

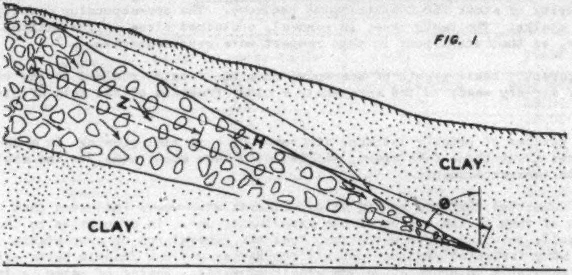

FIG. 1

opening into the soil at the point having potential $k\Phi$. As this tube passes from one potential-level to another the top of the water in it will generate a surface which has been designated the piezometric surface, and the equation of this surface giving h in terms of z may be expressed

$$h - h_o = a \cos \theta \ln[(H - Z)/H)]$$

where the symbol ln stands for the natural logarithm. The meaning of the symbols will be made clear from Figure 1. The constant a is related to the other quantities thus

$$a = (QH)/(\rho g A k)$$

Q representing the quantity of water flowing per unit of time, and A the cross-sectional area at the entrance.

(3) Flow toward an axis through uniform stratum bounded by parallel plane faces. In this case, the equation of the piezometric surface becomes

$$(h - h_o) = [Q/2\pi k\rho\ell g)] \ln (r/r_o)$$

In this equation the symbols have the same significance as in the previous equation, ℓ representing the distance apart of the bounding faces, r the variable distance from the axis, and r_o and h_o corresponding constant values of these two coordinates. The third one of the cylindrical coordinates, θ, disappears from the equation on account of the symmetry of the flow.

It is evident for this case that if the stratum is horizontal the gravity-term in the potential remains independent of the coordinate r and the gravity-field has no influence on the flow.

(4) In the case of a battery of such wells arranged in a circle, for distances remote from the axis of the battery the piezometric surface is similar to that for the single well but near the axis it is somewhat complicated. By a simple process of combining the potentials of the separate wells, the equation for this surface is shown to be

$$h = [Q/(2\pi n k \rho \ell g)] [n \ln(R_a/r) + \ln(G)]$$

where n is the number of wells of radius r in the battery arranged on a circle of radius R_a, and G is the finite product of trigonometric terms

$$G = \prod_{i=1}^{i=n} [1 + (R/R_a)^2 - 2(R/R_a)\cos(\theta + i2\pi/n)]$$

h, R, and θ being the cylindrical coordinates of the variable point. At the several walls of the individual wells the elevations of the piezometric surface will be the same. If we designate this height by h' and write the equation for the piezometric surface for a single well of radius R_e such that the flow is Q (the same as the aggregate flow for the battery) and such that its piezometric surface coincides with that for the battery at distances remote from the well, we have

$$h = [Q/(2\pi k\rho\ell g)] \ln (R/R_e) + h'$$

This radius R_e is defined as the radius of the equivalent single well.

(5) If drain-tile of a given diameter are installed at a given depth in homogeneous soil overlying an artesian stratum, the static water-head (or piezometric surface) being H feet above the ground surface, a definite relation between the excess head H and the distance apart of the drains s must exist in order that the pressure in the surface soil may be permanently reduced to zero. By combining the potentials for the drain regarded as a sink and for the uniform vertical flow from the gravel, the following relation in the form of an inequality has been derived

$$s < [2\pi wh(1 + H/w)/H \ln(s/2r)] \; .$$

where w is the thickness of uniform soil overlying the artesian stratum, h is the depth of the drain, and r is the radius of the tile.

(6) Taking into account the saving in cost of power in lifting water from large-diameter wells and of the advantage of the well-battery over the single well, the problem of efficient design of drainage-wells is considered with the conclusion that the efficiency increases with the effective diameter of the well.

(7) If irrigation-water is permitted to "sub" from an open ditch into a stratum of sand lying near the surface of the ground with clay underlying the sand, a part of the water seeps into the clay provided there is no artesian pressure underlying the clay. It is found possible by means of Darcy's law to compute the maximum distance the water can be expected to "sub" for given thickness of sand stratum if the transmission-constant of the sand and of the clay and the effective head of water in the "subbing" ditch are known. The following formula is developed

$$x = \sqrt{(2p_0 s k_s)/(k_c g \rho)}$$

where x is the maximum distance of "subbing", p_{ρ} is the pressure at the bottom of the "subbing" stratum of thickness s, at the canal "intake", k_s is the transmission-constant for the sand of the "subbing" stratum, and k_c is the transmission-constant for the underlying clay.

(8) In mountainous country with high rainfall much of the precipitation floods over the surface of the ground, giving rise to excessive erosion, the soil being insufficiently deep to absorb and carry away the moisture. By means of Darcy's law it is possible to develop a simple relation between the minimum depth of soil required and the rainfall-intensity on mountain slopes, the transmission-constant of the soil appearing as a parameter. Figure 2 will make clear the meaning of the formula. It is developed by equating the flux-integrals over the slope oa and over the arc ab, thus

$$\int_0^x i \cos \theta_1 dx = \int_{\theta_1}^{\theta_2} kg \sin \theta \, dz = \int_{\theta_1}^{\theta_2} kg \sin \theta \, x \, d\theta$$

This leads to the final formula

$$\cos \theta_2 = (1 - i/kg) \cos \theta_1$$

where i is the rainfall-intensity and k is the transmission-constant for the soil. The symbol x appearing as an upper limit in the first integral and in the argument of the last integral is the length of the section considered measured along the slope.

(9) The theory of capillary flow discussed heretofore by workers in this Laboratory presents a modified form of Darcy's law

$$v = k\rho\nabla\Phi$$

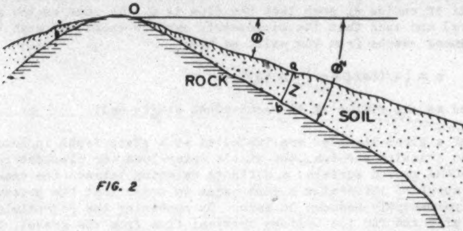

FIG. 2

together with a tentative empirical equation relating the capillary potential ψ to the moisture-content

$$\psi = c/\rho + b$$

These equations, together with the equation of continuity, are introduced into the problem of determining the loss by seepage from a circular canal and lead to the following non-linear second-order partial differential equation

$$\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial z^2} - \frac{2\rho}{c}\frac{\partial \rho}{\partial z} = 0$$

A solution due to Mr. H. G. Romig and Dr. G. R. Stiblitz of the Bell Telephone Laboratories is presented.

(10) This same theory is applied to the problem of determining the rate of drying out of a stratum of soil by downward percolation into the deeper soil. The following approximation formula is presented

$$Q = K + Le^{-\beta t} + Me^{-2\beta t}$$

where Q represents the quantity of moisture in a given depth of soil as a function of the time t, the constants, K, L, M, and β, being regarded as empirical.

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DISCUSSION OF "FUNDAMENTAL PRINCIPLES GOVERNING THE PHYSICAL CONTROL OF GROUND-WATER"

M. R. Lewis

The authors of this paper are to be complimented on the work they have done in showing the application of fundamental principles of mathematical physics to the ground-water problem. The writer is in complete sympathy with their viewpoint that better progress would be made in the practical control of ground-water if engineers in the field were aware of the physical laws which govern the movement of water through permeable material.

The facts that complete information as to underground conditions can not be secured and that even if such data were available their complexity would be such as to prohibit mathematical analysis are not valid excuses for complete disregard of the type of applications which are presented in this paper. An understanding of the character of flow which would occur under the idealized conditions presupposed in the theoretical treatment can not help assisting the practicing engineer in applying his judgment, as he must, to the particular problems and conditions he meets.

It is probable that many, if not most, practicing engineers in the drainage and water-supply fields would be more easily induced to study these applications by a somewhat simpler, if less rigidly formal approach. Ordinarily, two-dimensional flow is all that need be considered. By starting with a statement of Darcy's law in ordinary engineering terms, $Q = kA\ (H/L)$ and the use of comparatively simple mathematics most of the applications given in the paper may be reached.

The authors of the paper urge that engineers do not shy from the symbols and methods of the mathematical physicist; that is, that we, as engineers, use their language. There are undoubted advantages in that language, but I feel sure that their message will be more readily received in the field if they in turn make an effort to speak the language of the engineer.

The writer is particularly interested in two of the applications developed in the paper. We have learned by painful and expensive experience that a tile drainage-system will not serve to relieve a water-logged condition due to upward seepage of artesian water unless the artesian pressure is relieved. I think most of us had a rather vague idea of the reason for this phenomenon. The paper makes that reason clear. With such a clear picture of the idealized conditions we are not apt to try the impossible again.

Now for a final confession. Dr. Gardner and the writer have been corresponding for several months and have not yet reached an agreement as to the general truth of his conclusion in Problem 6 "that the efficiency increases with the diameter of the well." This is no argument against the desirability of the method but is, I think, a demonstration of the difficulties of long-distance discussion.

In conclusion, the writer hopes that the present authors and others will continue to work out these applications of fundamental physics to our practical problems in the control of water, both surface and underground. Always, however, close contact must be maintained with field-conditions or the theoretical results will fall far from the actual, because of some unforeseen factor. Perhaps the best example of what I have in mind is the problem of the wetting of dry soil. According to the usual approach the downward movement of moisture from a mass of soil at or near field-capacity into a mass at or below the wilting-point should be much more rapid than between an upper layer of the same higher moisture-content and a lower one at half way between the two moisture-contents. The writer believes, however, that the rate of flow in the second case is much more rapid.

Mr. Lee has shown the great variety of conditions in the field and these must be be carefully kept in mind in making applications.

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FLOW THROUGH GRANULAR MATERIALS

G. H. Hickox

Summary--This paper outlines a rational method of attack on the problem of stream-line and turbulent flow through granular materials. It relates the friction coefficient f, and Reynolds' number R_e, to the terms applied to flow in pipes, and compares experimental results with the theory.

Notation--a = cross-sectional area; A = surface-area; $c_1 = \ell_p/\ell$; d = diameter of pipe or stream-tube; d_s = diameter of sphere or sand-grain; f = coefficient in Weisbach's formula; g = acceleration of gravity; h = head-loss in feet of fluid flowing; k = coefficient; ℓ = length of pipe or soil-column; ℓ_p = length of stream-path; n = number of spheres or sand-grains; p = porosity of material; P = per cent of sand by weight, having a given diameter; Q = rate of discharge; r = hydraulic radius; R_e = Reynolds' number; S = shape-factor; v = apparent mean velocity = Q/a; v_m = apparent mean pore-velocity = Q/ap; v_p = true mean pore-velocity; V = gross volume; V_p = volume

of flow or pore-space; V_s = volume occupied by material; μ = absolute viscosity; υ = kinematic viscosity; and ρ = density.

Theory--The earliest investigators [see reference 2 at end of paper] of the flow of fluids through granular materials assumed that the drop in pressure or head-loss was directly proportional to the rate of discharge or velocity. Their studies were confined to the flow of water and did not consider the effect of temperature. Viscosity was later introduced and Poiseuille's law of viscous flow was applied [9]. More recently with the growth of interest in oil-recovery, the older formulas have been revised and extended to include the flow of oil and gas as well as water. Those studying comparatively high rates of flow have found that the head-loss varies as some power of the velocity greater than one. This has led to the idea of turbulent flow and a relationship between dimensionless moduli as in the case of flow in pipes [1, 4, 6].

If we consider the flow of fluid through a granular material as being analogous to that through pipes, we find no lack of available formulas. The only difficulty lies in establishing the analogy. The use of Weisbach's formula and a relation of the friction-factor to Reynolds' number has led to an excellent correlation of results in pipe flow. This formula is

$$h = f(\ell_p/d)(v_p^2/2g) \tag{1}$$

where $f = f(R_e) = f(v_p d/\upsilon)$. In the case of pipes, the values of ℓ_p, d, and v_p can be determined quite satisfactorily. For a granular material, the conditions are somewhat different.

The length of the path of flow in a pipe is the length of the pipe between measuring sections. For granular materials, the length of path is evidently somewhat longer. Let the true length of path be related to the apparent length by the equation

$$\ell_p = c_1 \ell \tag{2}$$

The mean velocity of flow through a pipe is $v = Q/a$ and the mean velocity of flow through granular material is $v_m = Q/ap$, but this is only the velocity averaged in the general direction of flow. The true mean velocity in the pore-spaces will be in proportion to the length of path or $v_p = Qc_1/ap$. If we let $v = Q/a$ denote the apparent mean velocity through granular material, that is, the discharge divided by the gross area, then

$$v_p = vc_1/p \tag{3}$$

The diameter of the pore-spaces may be arrived at roughly as follows: For a cylindrical pipe, we can compute the hydraulic radius as equal to the cross-sectional area divided by the wetted perimeter. For a circular pipe this is

$$r = (\pi d^2/4)/\pi d = d/4$$

That is, the diameter is four times the hydraulic radius. Now if we multiply both numerator and denominator of this expression by ℓ, we have

$$r = (\pi d^2 \ell/4)/\pi d \ell = V/A = V_p/A \tag{4}$$

or the volume of the pipe divided by the surface-area. For an assemblage of spheres, we can compute the ratio $r = V_p/A$ and from this arrive at a "diameter" analogous to pipe diameter by simply multiplying by 4. The volume occupied by the spheres is

$$V_s = n\pi d_s^3/6$$

and the flow-volume is

$$V_p = [p/(1 - p)](n\pi d_s^3/6)$$

The surface-area is

$$A = n\pi d_s^2$$

Then

$$r = V_p/A = [p/(1 - p)](d_s/6)$$

and

$$d = 4r = (4d_s/6)[p/(1 - p)] \tag{5}$$

The ratio $d_s/6$ is the ratio of volume to surface-area for a sphere and in general we can say for solids of any shape that the ratio of volume to area is d_s/S where S is a shape-factor which is 6 for the special case of a sphere.

With these values of ℓ_p, v_p, and d, we can rewrite the Weisbach formula

$$h = f(c_1^3S/4)[(1 - p)/p^3](\ell/d_s)(v^2/2g) \tag{6}$$

or

$$h = k(\ell/d_s)(v^2/2g) \tag{7}$$

where

$$k = f(c_1^3S/4)[(1 - p)/p^3] \tag{8}$$

Likewise the corresponding Reynolds' number becomes

$$R_e = (vd_s/\nu)(4/S)[c_1/(1 - p)] \tag{9}$$

For viscous flow, Poiseuille's law should hold

$$h = 32\,\mu\ell_p v_p/\rho g d^2$$

Equating this expression to equation (6) and solving for f, we have

$$f = (32\,\mu\ell_p v_p/\rho g d^2)(4/c_1^3S)[p^3/(1 - p)](d_s/\ell)(2g/v^2)$$

Substituting for ℓ, v, and d from equations (2), (3), and (5), this reduces to

$$f = 64\,\mu/v_p d\rho = 64/R_e \tag{10}$$

which is the familiar relation between friction-factor and Reynolds' number for viscous flow in pipes.

Equations (6) and (9) were developed for a material of uniform size. If the material is not uniform, as is generally the case, then some single diameter representative of the mixture must be chosen. Fair and Hatch [3] have shown that where the shape-factor is the same for all sizes in a mixture

$$d_{s\,(eff)} = \Sigma P/\Sigma(P/d_s) \tag{11}$$

This diameter is known as the "effective diameter" and is the diameter of a group of uniform particles having the same surface-area, volume, and shape-factor as the mixture. Since these are the only properties of the material which enter the equations, this effective diameter may be used in all cases.

Figure 1 shows equation (10) plotted on logarithmic coordinates where it appears as a straight line. Values of friction-factor and Reynolds' number determined experimentally for the viscous flow of fluids in pipes having a large range of surface-roughness agree well with this theoretical curve. Turbulent flow, however, can not be represented for all pipes by one curve, but requires a separate curve for each degree of roughness. A portion of the curve for smooth lead pipe is shown at the extreme right of Figure 1. It will be noted that the transition from viscous to turbulent flow in pipes takes place between Reynolds' numbers of about 2000 to 3000, the transition being abrupt and very decided.

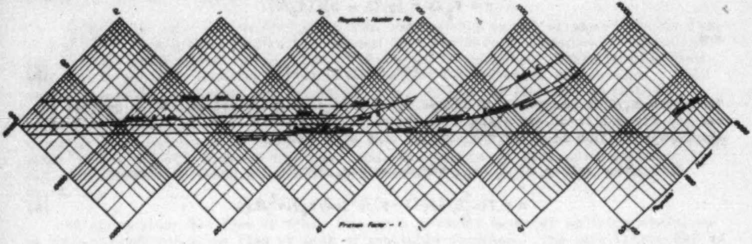

Fig. 1

Experimental results--In order to compare tests on flow through granular materials with this curve for pipe-friction, it is necessary to evaluate the coefficients c_1 and S. If the theory developed is correct, knowledge of their values should enable us to calculate values of f and R_e that would agree with the results obtained on pipes. For spheres, the value of S is definitely 6. For other shapes, it must be larger, if based on the diameter of a sphere of equivalent volume. The value of S for any particle depends on the particular diameter used to specify the size and it is by no means certain that the clear opening of a standard sieve corresponds to the diameter of a sphere of volume equal to that of particles just passing the sieve. Fair and Hatch [3] have evaluated the shape-factor S for a number of sands ranging from "sub-rounded" to "angular" and found that S varies from 6.4 to 7.7 for diameters based on sieve-analyses. The correct value, however, is quite uncertain and for the purpose of comparison of results, all the materials used were assumed to have the properties of spheres and a factor of 6 was used. The length of path is also an uncertain quantity. Slichter [9] has evaluated it for certain conventional arrangements of spheres. For the purpose of present calculation, c_1 was assumed 1.3, which is the value given for the most compact arrangement of spheres.

Figure 1 shows the results of tests. Solid lines represent tests on uniform materials and their characteristics are summarized in Table 1.

Table 1--Characteristics of uniform materials

Investigator	Material	Range of diameter	Fluid	Range of porosity (per cent)
Givan [5]	Lead shot	No. 5, A R, OOB	Water	35.7 to 42.1
Fancher and Lewis [4]	Lead shot	0.00328 ft	Oil	34.5
Hulburt and Feben [6]	Ottawa sand	0.00094 to 0.00336 ft	Water	35.2 to 38.7
Miller and Law [8]	Monterey beach-sand	0.000704 to 0.00150 ft	Oil	35.0
Hickox (Curve B)	River-gravel	0.00815 ft	Water	35.0
Lindquist [7]	Lead shot		Water	38.0

It will be noted that there is fair agreement between the curves for uniform materials with the exception of the data by Hulburt and Feben and by Fancher and Lewis. The discrepancy in the case of the former is not surprising as the porosity given for their materials was not measured in place for testing but in separate tubes. The reason for the divergence of the data by Fancher and Lewis is not known. The heavy broken line represents an extension of Lindquist's equation [7] by the method outlined in this paper. It agrees well with Givan's data on lead shot but is somewhat lower than the data of Miller and Law, and Hickox for sand. This is to be expected since the sands must have a shape-factor greater than 6 which would lower the curve somewhat.

The agreement with Poiseuille's law for viscous flow is not perfect. It is reasonably good, however, in view of the assumptions made. The discrepancy may be due to a loss of head caused by alternate expansion and contraction of the fluid stream passing through the pore-spaces. Little is known about such losses in viscous flow although Chilton and Colburn [1] have estimated the resistance due to this cause as 80 per cent of the total head-loss, only the remaining 20 per cent being due to friction. In view of the agreement shown in Figure 1, this would seem to be excessive for uniform materials.

The dashed lines represent data and tests on graded materials. Their characteristics are given in Table 2. These tests do not agree as well, the friction-coefficient being considerably higher. This may be attributed to three causes: (1) The shape-factor for these sand-mixtures is greater than 6; (2) the length of path is greater for mixtures than for uniform materials; (3) the loss due to expansion and contraction may be greater, due to greater variations in the pore-spaces.

Table 2--Characteristics of graded materials

Investigator	Material	Mean diameter	Fluid	Range of porosity (per cent)
Hulburt and Feben [6]	Ottawa and miscellaneous sands	0.00135 to 0.00280 ft	Water	33.9 to 48.4
*Miller and Law [8]	Monterey beach-sand	0.000960 to 0.00142 ft	Oil	35.0
Hickox (Curve A)	Belgian glass-sand	0.000865 ft	Water	40.2
Hickox (Curve C)	River-gravel	0.0378 ft	Water	36.5
Hickox (Curve D)	San Francisco bar sand	0.000442 ft	Water	49.8
Hickox (Curve E)	Carmel beach-sand	0.000832 ft	Water	45.1
Hickox (Curve F)	American River sand	0.00150 ft	Water	43.3 to 48.4

*Artificial mixtures of two uniform sizes.

It appears that a better knowledge of (1) the shape-factor of various materials, (2) the length of the path of flow in mixtures, and (3) the relation of actual size of particles to sieve-openings, would permit a reasonably close calculation of the flow through granular materials on the basis of the well-established Weisbach equation for pipe-flow.

Further investigation should be made along the lines of determining these variable factors in terms of easily measured quantities such as sieve-analyses and specific gravity. The work of Fair and Hatch, already mentioned, and of Wadell [10] in determining the area-volume ratio by means of Stokes' law are important steps in this direction.

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FLOW OF WATER THROUGH GRANULAR MATERIALS--INITIAL EXPERIMENTS WITH LEAD-SHOT

C. V. Givan

Introduction--While it is well known that granular materials in ground-water-bearing strata are not composed of uniform spheres, it is believed that further work under simplified conditions with material such as lead-shot will be useful to those who from necessity make observations on complex mixtures of naturally deposited porous materials. The preliminary work reported here was done in the University of California Hydraulic Laboratory by the writer for the Agricultural Experiment Station, by arrangement between the Division of Irrigation Investigations and Practice, College of Agriculture, and the Department of Mechanical Engineering, University of California.

A more detailed report of the work done was included in a thesis presented to Stanford University in June 1933. Professor M. P. O'Brien, in charge of the University of California Hydraulic Laboratory, was interested in the problem before the arrangements to use equipment in the laboratory were made. Professor O'Brien's translation of an unpublished manuscript which described work done under the direction of Dr. Erik Lindquist in the Hydraulic Laboratory of the Royal Technical University, Stockholm, was very helpful. Following completion of the thesis in which these initial experiments with lead-shot were described, Lindquist's paper appeared with several changes and additions, as a communication to the First Congress on High Dams, Stockholm, and has become available recently in the Transactions of the World Power Conference.

It is of utmost importance to emphasize that the fluid flows through the pore-spaces and not through the material itself, as Slichter was so careful to do in his chapter on the "Laws of rectilinear flow of ground-water through a soil" (U.S.G.S. 19th Ann. Rep., Part II). Before real progress can be made, it will be desirable to determine whether or not Slichter's porosity-function is dependable for uniform spherical particles. Recently, W. O. Smith has developed a formula which fits the experimental data of Green and Ampt fairly well over a narrow porosity-range. The work of C. C. Furnas, "Flow of gases through beds of broken solids," published in 1929 by the United States Bureau of Mines as Bulletin 307, contains valuable contributions to this subject.

Apparatus--A detailed description of equipment and procedure will be included in another paper now being prepared. Figure 1 is a photograph of the 6-inch tube.

Experiments reported--Measurements were made of the pressure required to force water through three sizes of pipe filled successively with three sizes of lead-shot. The packing of the shot was changed as much as possible by moderate shaking of the pipe so that observations could be made with different known average porosities.

Table 1--Summary of sizes of pipe and shot and of extreme range of porosities

Pipe-sizes		Shot-sizes		Extreme range of average porosities in each tube
Approx. inside diameter	Distance between pressure-taps	Commercial grade	Mean diameter	
inch	feet		mm	per cent
2	2	No. 5	3.00	42.0 - 36.2
4	4	Air-rifle	4.29	40.5 - 37.7
6	3.28	00 balls	8.38	37.3 - 35.7

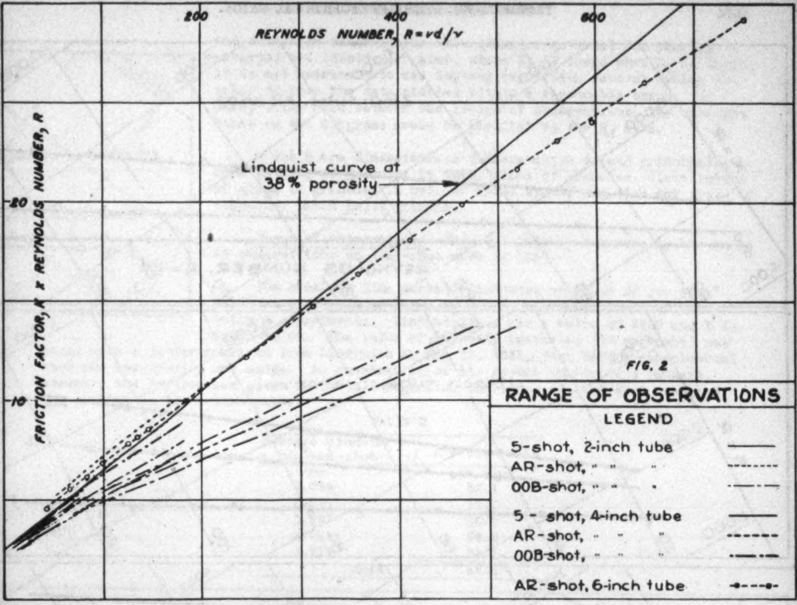


FIG. 2

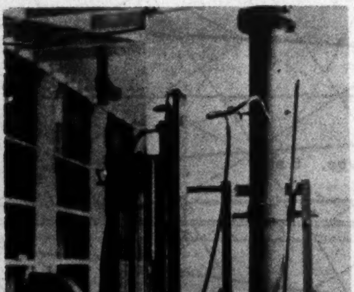


Fig. 1

Measurements were compared, as was done by Lindquist, by showing the relationship between a dimensionless friction-factor, K_d and a Reynolds' number R_d.

$$K_d = (2g/v^2)\ d\ (H/L) \qquad (1)$$

$$R_d = vd/\upsilon \qquad (2)$$

where g = acceleration of gravity in feet per sec^2; d = average spherical diameter of shot in feet; H = pressure-head measured by height of fluid manometer in feet; v = average velocity in tube filled with lead-shot in feet per second (velocity based on total internal area of tube); L = distance between pressure taps in feet; υ = kinematic coefficient of viscosity in $feet^2$ per second.

For convenience, $K_d \times R_d$ has been plotted as a function of R_d. Consequently, the "straight lines" shown in Figures 3 to 6, which follow, represent the equation

$$K_d = (A/R_d) + B \qquad (3)$$

The principal advantage of this method of representation is that straight lines drawn through plotted points with coordinates $K_d \times R_d$ and R_d fit fairly well the data obtained from a series of head-loss

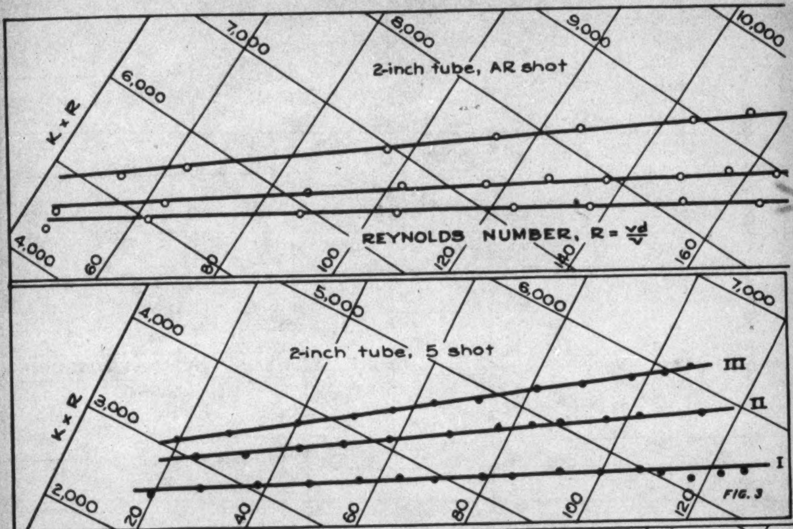

2-inch tube, AR shot
K × R
4,000
6,000
7,000
8,000
9,000
10,000
REYNOLDS NUMBER, R = vd/ν
60
80
100
120
140
160
2-inch tube, 5 shot
K × R
2,000
3,000
4,000
5,000
6,000
7,000
III
II
I
20
40
60
80
100
120

FIG. 3

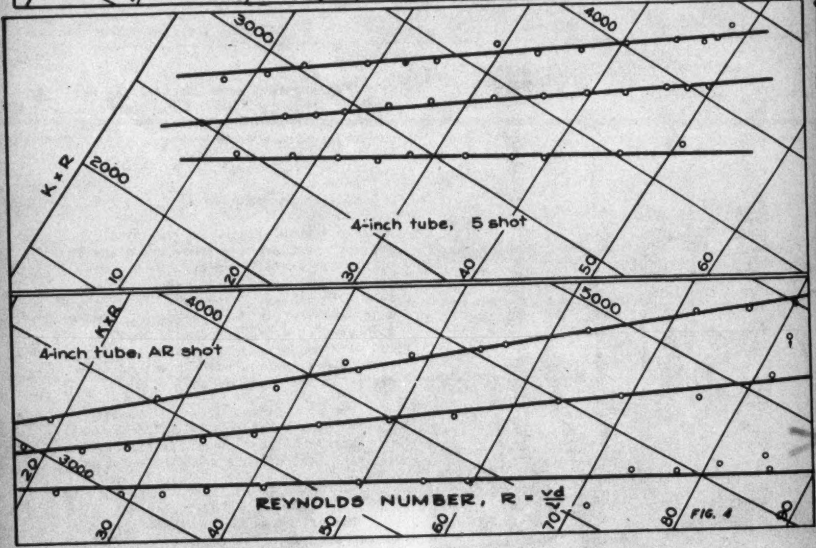

4-inch tube, 5 shot
K × R
2000
3000
4000
10
20
30
40
50
60
4-inch tube, AR shot
K×R
3000
4000
5000
REYNOLDS NUMBER, R = vd/ν
20
30
40
50
60
70
80
90

FIG. 4

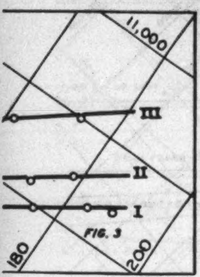


FIG. 3

and discharge observations when granular material and packing of material are identical. Also, since K_d is large when R_d is small, it is not necessary to use log-log paper with several cycles in order to keep the data plotted within a reasonable space. If Darcy's law held between the limits of observations, the straight lines on the diagrams would be parallel to the R_d axis.

A and B are dimensionless numbers which depend principally upon packing of granules in tube, shape of granules, distribution of sizes of granules in beds of mixed sizes, and size and shape of container which holds granules.

Range of observations--Figure 2 indicates generally the range of observations on lead-shot made in 1933.

The straight line marked "Lindquist curve at 38 per cent" has been extrapolated above $R_d = 180$, the upper limit of Lindquist's experiments. Lindquist's A has a value of 2500 and B is equal to 40. The value of porosity indicated (38 per cent) was based upon a letter received from Lindquist on May 15, 1933, just before experimental work was temporarily set aside. An examination of his recent publication reveals, however, the information given in Table 2 regarding the sizes of lead-shot used and the packing in his 4-inch tubes.

Table 2

Average diameter of lead-shot	Average voids
mm	per cent
1.054	37.1
2.037	39.1
2.993	38.1
4.019	39.0
4.919	38.1
Mean	38.3

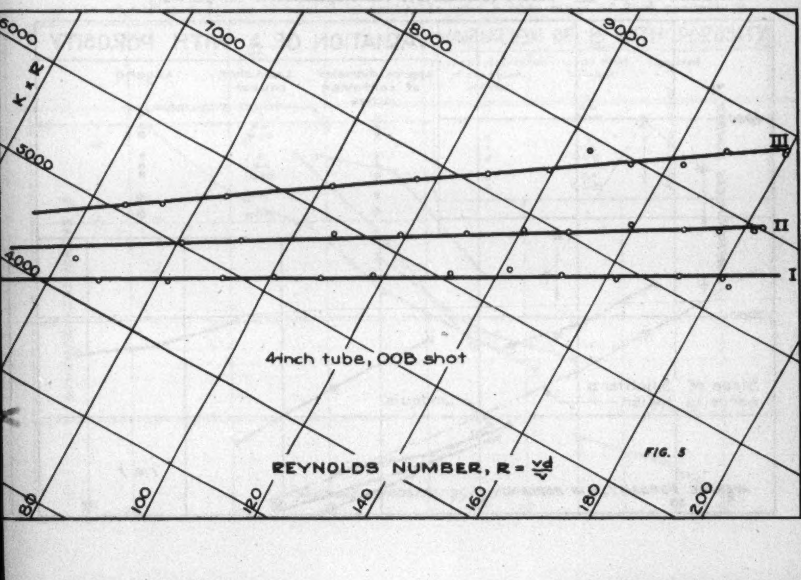
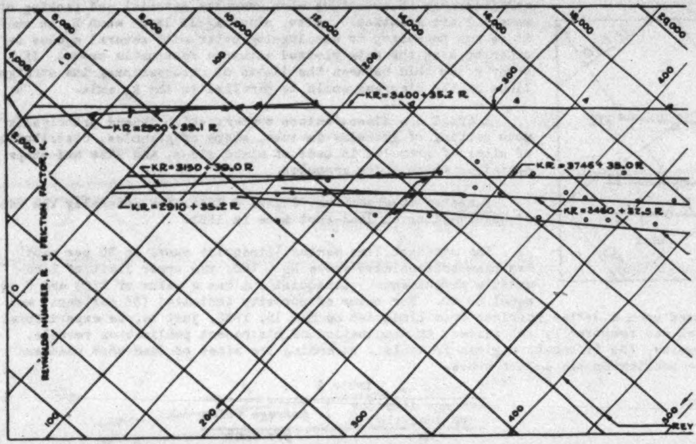


FIG. 5



Discussion of experimental work--Data have been plotted on Figures 3 to 6. If the equation $K_d = [(A/R_d) + B]$ holds, then the values of $K_d \times R_d$ when shown as a function of R_d should follow a straight line, the projection of which intersects the coordinate axis $R_d = 0$ at the point A. B is the slope of the line. (In order to reduce the size of Figs. 3 to 6, the diagrams have been rotated so that the "straight lines", determined by the "$\Sigma\Delta$" method (Steinmetz), run lengthwise of the plates.)

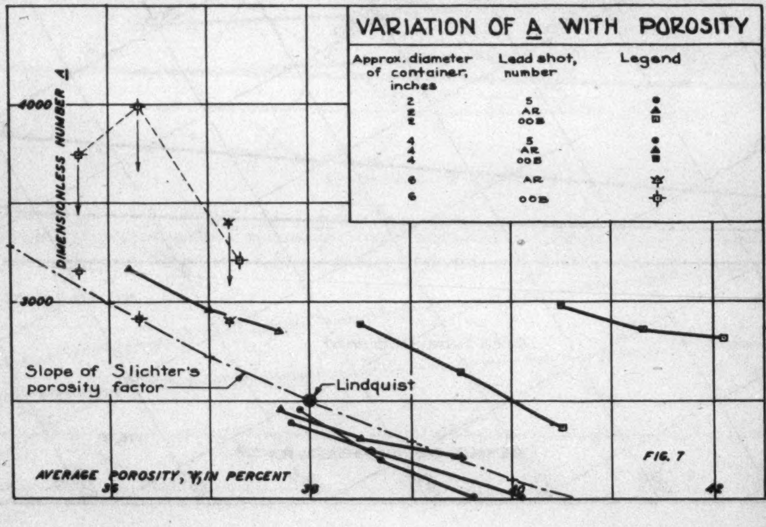


FIG. 7

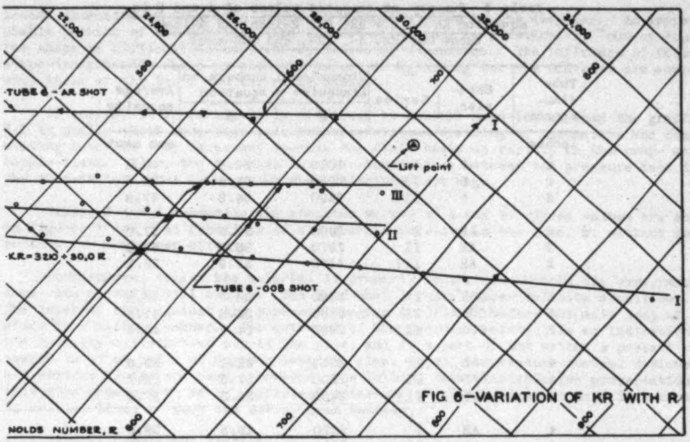
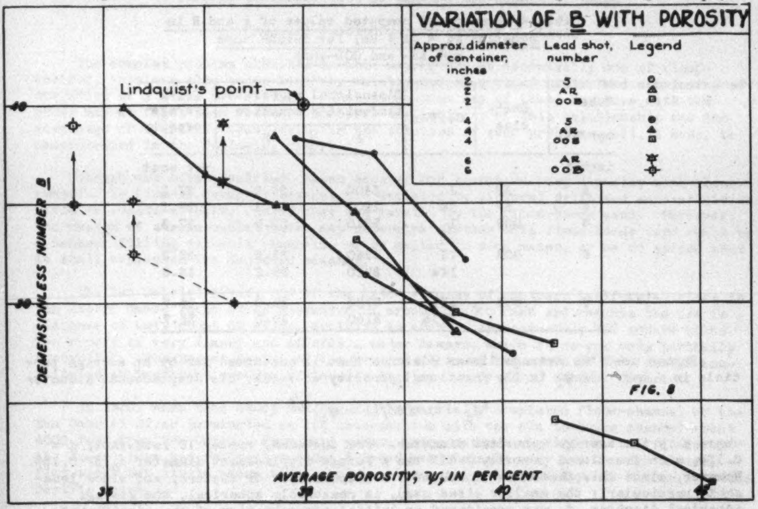


FIG. 6—VARIATION OF KR WITH R

The positions of the points shown on these Figures indicate that observations between Reynolds' numbers 150 and 20 follow rather closely the straight lines drawn. Consistent departures, which the writer as yet has not been able to attribute to observational errors, become evident at both higher and lower Reynolds' numbers.

It is by no means certain that use of the average spherical diameter of the shot d as the significant linear dimension is desirable over a wide range of R or porosity ψ.



VARIATION OF B WITH POROSITY

FIG. 8

Table 3--Summary of computed values of A and B in equation KR = (A + BR) for 2-inch and 4-inch tubes and No. 5-, AR-, and OOB-shot

Tube diam. approx.	Shot-size	Series	Dimensional numbers in Lindquist's equation		Average porosity
			A	B	
inches					per cent
2	5	I	2010	27.4	40.1
2	5	II	2250	31.4	38.6
2	5	III	2390	34.8	37.8
2	AR	I	2860	34.9	37.7
2	AR	II	2970	36.5	37.0
2	AR	III	3170	39.9	36.2
2	OOB	I	2820	20.9	42.1
2	OOB	II	2860	22.8	41.3
2	OOB	III	2980	24.1	40.5
4	5	I	2010	32.2	39.6
4	5	II	2200	37.5	38.7
4	5	III	2460	38.3	37.9
4	AR	I	2220	28.5	39.5
4	AR	II	2310	34.6	38.5
4	AR	III	2460	38.4	37.7
4	OOB	I	2370	27.9	40.5
4	OOB	II	2650	29.5	39.5
4	OOB	III	2890	33.2	38.5

Table 4--Summary of computed values of A and B in equation KR = (A + BR) for 6-inch tube and AR- and OOB-shot

Tube diam. approx.	Shot-size	Series	Dimensional numbers in Lindquist's equation		Average porosity
			A	B	
inches					per cent
6	AR	I	3400	35.2	37.2
6	AR	Ia	2900	39.1	37.2
6	OOB	I	3210	30.0	37.3
6	OOB	II	3460	32.5	36.3
		IIa	2910	35.2	36.3
6	OOB	III	3750	35.0	35.7
		IIIa	3150	39.0	35.7

Furnas used the average linear distance that is accounted for by an average particle in a bed. If ψ_1 is the fractional porosity or voids, his displacement diameter

$$d_d = 0.806d/(1 - \psi_1)^{1/3}$$

where d is the average spherical diameter. For instance, number 12 lead-shot, d = 0.138, with fractional porosity 0.419 has a Furnas displacement diameter d_d of 0.133. However, since this factor is linked with a shape-factor or factors, and since lead-shot, particularly the smaller sizes used, is reasonably spherical, the average spherical diameter, d, was considered an initial approximation of the significant linear dimension in computing values of K_d and R_d shown in the diagrams. An appreciable portion of the OOB-shot, the largest size used, is considerably "out of round." The shape is difficult to describe by ratios of dimensions. The influence of this shape-irregularity shows up when the values of K_d and R_d for the OOB-shot are compared with those of the No. 5 and air-rifle sizes.

Of course, it is particularly difficult to measure head-losses when the gradient H/L is small. With very high velocities, persistent draining of manometers and connecting tubes is very necessary because the fluid heats up rapidly in the pump- and supply-lines. Also, the increase in water-temperature between the pressure-taps in the shot-filled tubes is apparent when velocities are high.

Tables 3 and 4 summarize the computed values of A and B. These values are shown in Figures 7 and 8 as functions of the average porosity in the tube, ψ, without correction for container effect.

Furthermore, unless the material is properly restrained within the experimental tube its porosity will change. The lead-shot "floats" under definite conditions. The layer of shot against the pipe-wall begins to "float" before the main body of shot rises in a uniform manner. The movement of the granular material is an indication of the velocity-distribution across the pipe, and is a part of the writer s present research in which balls of various density, glass pipes, temperature-control devices, and various fluids are used. However, the initial data available for presentation at this time appeared to be of sufficient interest to publish since so many investigators in related lines of work are making such headway.

Agricultural Experiment Station,
University of California, Berkeley, California

SOLVING A FLOOD AND BEACH PROTECTION PROBLEM WITH AN HYDRAULIC MODEL--A STUDY OF SAN GABRIEL RIVER MOUTH AT ALAMITOS BAY INLET, CALIFORNIA

Charles T. Leeds, Vito A. Vanoni, and Robert T. Knapp

(a) Physical Conditions, by Charles T. Leeds

The complex problem sketched in this paper, though essentially one of flood-control, involves also ocean-beaches, maintenance of a tidal basin, and continuity of operation of a steam power-plant. What connection any of these may have with the other may at first seem remote. However, the intimacy of this relationship and the advantage of hydraulic model-tests in the solution of such problems will, I hope, be demonstrated in the following paper.

Though not often realized, beach erosion and accretion vary directly with flood-runoff. In time of drought, beaches are depleted by littoral drift and wave-attrition while in season of heavy runoff they are rebuilt by the flood-borne sand. Moreover, the design of stream-outlet works may determine whether this flood-borne sand shall be a menace, filling valuable channels, or be wasted in deep water, or be so guided that it shall replenish the depleted beaches.

The San Gabriel River, one of the major streams of southern California, rises in the Sierra Madre range at an elevation of around 10,000 feet and reaches the sea in a distance of only about 50 miles, draining an area of approximately 700 square miles. The runoff is very flashy and affords a major hazard, which is as yet only partially controlled. The proper design of the control-works at the mouth of this stream constitutes an important problem of the Los Angeles County Flood Control District.

In 1930, when this study was begun, the partially completed flood-channel of the San Gabriel River terminated at its intersection with the old tortuous channel about 4000 feet from the Ocean. From this point, under natural conditions, the floods of the lower river had followed various ill-defined channels over and through a wide, flat area, but little above tide-level, emptying into Alamitos Bay and thence into the Pacific Ocean.

This great area around the Bay has, in the last 10 or 15 years, undergone extensive real-estate improvement, with installation of many oil-wells. The potential flood-loss from overflow was therefore very great. Also, the River was liable to cut a more direct route to the Ocean or, by surcharging the capacity of the Bay, to break through the narrow sandspit near the westerly end of the Bay.

Alamitos Bay Inlet, like the mouths of most lagoons on a sandy coast, has migrated back and forth between the westerly point mentioned and its present location.

In 1924 the Los Angeles Gas and Electric Corporation constructed a steam power-plant at the easterly edge of the Inlet because of the assured supply of sea-water for cooling purposes. This plant, with a present capacity of 65,000 kilowatts, later to be trebled, with an ultimate requirement of 700 second-feet of cooling water, serves a large metropolitan area. Hence the vital importance of assuring its continuity of operation.

An inner sand-bar had developed just within the Inlet. This area had been acquired by the State for development as a marine park.

These were the physical conditions in 1930 when the Flood Control District sought to condemn a right of way for an approximately straight flood-channel from the point above mentioned to the Ocean alongside the power-plant through Alamitos Bay Inlet. Because of the combined menace (a) of undermining the foundations of the power-plant and the adjacent high-tension transmission-tower, and (b) of clogging the cooling water intake with sand, either of which might cause protracted interruption of service, the power-corporation filed answer claiming anticipated damages in excess of $10,000,000.

At this point the author was called in as consultant by the Flood Control District. The power-corporation, though at first strongly opposed to the District's plans, not only changed its attitude on learning that a really scientific study was to be made of the problem with full consideration of the prior rights of the power-corporation, but also cooperated most generously, as will be shown later.

Previous studies by the District had indicated a probable maximum flood-peak of 60,000 second-feet. Surveys and current-observations at Alamitos Inlet showed a maximum tidal discharge of 6500 second-feet. Anemometer-observations and float-studies had also been carried on and several contour-surveys of the shore were made to show beach-changes.

Analyzing the problem which presented itself, the following objects were to be attained: (1) A flood-channel of adequate capacity and direct alignment; (2) protection of power-plant and transmission-tower from undermining; (3) assurance of an adequate and continuous supply of cooling water for the power-plant; (4) protection of Alamitos Bay against shoaling; (5) protection of marine park-area from erosion; (6) assurance against choking of the inlet-mouth; (7) control of flood-borne sand at shore-line so as to build up adjacent beaches rather than wasting it in deep water beyond wave-action; (8) outlet works, or jetties such as will minimize beach erosion through interruption of littoral drift. These will be discussed consecutively.

The design of an adequate and safe flood-channel was reasonably simple, bearing in mind the differences in specific gravity of salt water and fresh water and the back-water curve, though the exigencies of right-of-way alignment necessitated an undesirable reverse curve.

Protection of power-plant and transmission-tower foundations was also simple, using steel sheet-piles and rip-rap bank protection, although requiring experience and judgment to attain adequate protection without undue expense.

Assurance against interruption of cooling-water supply could have been most simply accomplished by excluding the River from the Bay and by constructing an inverted siphon under the River from the power-plant to the Bay. This would have been unduly expensive, however. Therefore, there was attempted the more difficult task of so directing the River and tidal currents as to accomplish all desired ends.

To protect Alamitos Bay against shoaling and to protect the proposed marine park-area just within its mouth, the first thought was to control the flood-currents by channel-bank alignment. The District's plan contemplated confining the flood-flow between heavily rip-rapped embankments, the channel-alignment approaching Second Street bridge from the north on a curve of 1800-foot radius, to bring the current past the power-plant parallel to the bulkhead already protecting the plant, which, however, was to be strengthened. From the Second Street bridge to the Ocean Avenue bridge the channel was between parallel rip-rap levees, leaving a gap in the westerly levee for the tidal flow of Alamitos Bay. The levees on either side of this gap were extended westerly into the Bay a short distance with a view to directing the current. Seaward of the Ocean Avenue bridge parallel jetties were to be constructed perpendicular to the bridge, for an initial distance of 600 feet or to a depth of -1.0 foot. These were to be extended later, in 500-foot units, as might prove advisable. The distance between levees at and seaward of the Ocean Avenue bridge was to be about two-thirds of the natural ocean-mouth width.

This plan would clearly have protected the proposed marine park-area, assured against choking of the River mouth, delivered the flood-borne sand at the beach-line, and avoided interference with littoral drift. Any extension of the jetties was then and still is felt by the writer to be inadvisable. The gap in the westerly levee was recommended to be so re-located as to direct the ebb-tide flow from Alamitos Bay toward the power-plant intake, and thus foster maintenance of deep water there.

Certain changes in location and alignment of the levees were recommended to increase the efficiency of control of currents and sand-deposits. However, realizing the futility of attempting to solve any such complicated hydraulic problem by mathematical means, the author strongly advised a study with an hydraulic model.

Through concurrence of the Flood Control District and the power-corporation in this procedure, a cooperative agreement was effected whereby the latter would make the model-studies through the agency of the California Institute of Technology. The District agreed to contribute $1000 (no more being possible because of limited funds) and the power-corporation to contribute the remainder of the expense, which finally aggregated approximately $4300.

An agreement was also effected between the District and the Federal Beach Erosion Board for a cooperative study of beach-problems at the mouths of the three major streams of the county, coordinating flood-control with beach-protection. Therefore, the model-studies included also this latter objective.

The problem was far from simple, involving the combined variables of flood-flow, flood-borne sand, tidal flow, and tidal stage. The limits of variation of the first were from 0 to 60,000 second-feet; of the second from 0 to an unknown maximum; of the third from a maximum ebb-flow of 6500 second-feet to a maximum flooding-tide flow somewhat less; and tide-stages from -2.5 to +8.0 feet. Combined with these were uncertain factors of wind, wave, and ocean-currents, variable in direction and magnitude.

The construction of the model and the prosecution of the tests were carried on under the direction of Professor Robert T. Knapp by Vito A. Vanoni, with the consulting advice of the author. Attention is invited to the able reports of these gentlemen for details of the tests and the conclusions drawn therefrom.

(b) Apparatus and Technique of Model-Study, by Vito A. Vanoni

Introduction--This paper deals only with the apparatus and technique employed in the study of the problem in the laboratory. Some of the more interesting apparatus and methods are described in an attempt to acquaint the reader with the problem as seen from the experimenter's point of view.

General description of laboratory--Figure 1 shows a diagram of the laboratory which is built out of doors on the campus of the California Institute of Technology at Pasadena, California. The floor-space available for the construction of models is 40 feet by 40 feet with a projection on one side of 14 feet by 20 feet. This area has a concrete floor and is enclosed by concrete walls 18 inches high. There are three

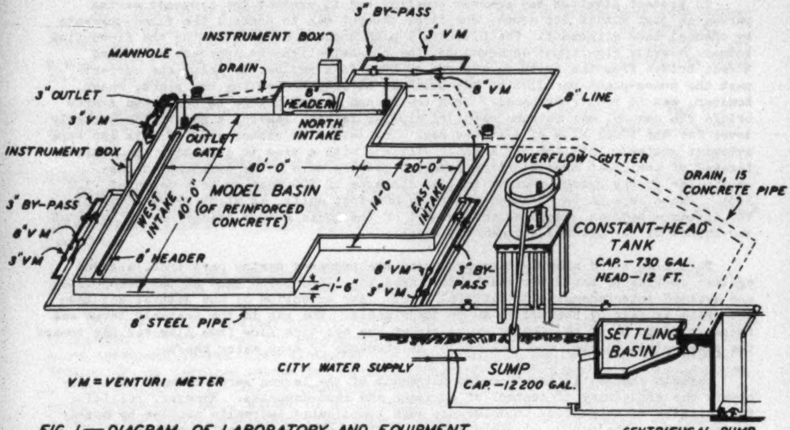

3" BY-PASS
INSTRUMENT BOX
3" VM
MANHOLE
DRAIN
8" VM
8" LINE
3" OUTLET
8" HEADER
3" VM
NORTH INTAKE
INSTRUMENT BOX
OUTLET GATE
OVERFLOW GUTTER
40'-0"
20'-0"
DRAIN, 15 CONCRETE PIPE
MODEL BASIN (OF REINFORCED CONCRETE)
3" BY-PASS
WEST INTAKE
40'-0"
14-0
EAST INTAKE
CONSTANT-HEAD TANK
CAP. — 730 GAL.
HEAD — 12 FT.
8" VM
3" VM
8" HEADER
8" VM
3" VM
3" BY-PASS
1'-6"
8" STEEL PIPE
SETTLING BASIN
CITY WATER SUPPLY
SUMP
CAP. — 12 200 GAL.
VM = VENTURI METER
CENTRIFUGAL PUMP

FIG. 1—DIAGRAM OF LABORATORY AND EQUIPMENT, HYDRAULIC STRUCTURES LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA

intakes (north, east, and west) at which water can be supplied or withdrawn. Water is pumped from the sump-tank into the high-head tank. The water that is not taken into the system runs over the top of the tank, is collected by the overflow gutter, and returns to the sump through the down-spout. The 8-inch steel feeder-pipes supply the water to each of the three intakes. Water is admitted evenly over the full width of the intake by means of slotted 8-inch header-pipes placed in the bottom of intake-troughs about two feet wide and two feet deeper than the floor of the model-basin. Water that is withdrawn runs back to the sump through a 15-inch concrete pipe and is recirculated.

Each intake is equipped with an 8-inch and a 3-inch venturi meter for measuring flows. With the two different-sized meters it is possible to measure flows over a wide range with fairly uniform accuracy. Two of the outlets are also equipped with 3-inch venturi meters for measuring outflow.

Figure 2 shows one of the instrument boxes with which each intake is equipped. A water-manometer for reading the pressure-differential on the 3-inch venturi tube is shown on the right. A point-gage which was developed by Professor Knapp for this laboratory is shown on the left. It consists of a micrometer graduated to five ten-thousandths of a foot to which is clamped a stainless steel rod extending down to the water-surface in the glass stilling-well. By clamping the micrometer to grooves in the rod passing through it, the gage is made to read over a large range. When the point makes contact with the water, a 110-volt circuit containing a neon-tube is completed and the tube lights. It was found possible to measure a still-water surface accurately and rapidly to well within five ten-thousandths of a foot with this instrument.

Operating technique: (1) Construction of model--Figure 3 shows the model of the Alamitos Bay in the laboratory. The lower side represents the Ocean. The Bay extends to the left from the intake. The banks or shore-lines are about nine inches high and are made of about 1 : 12 concrete, the surface of which is water-proofed with a cement wash. The model was molded in fine sand to a horizontal scale of 1 : 120 and a vertical scale of 1 : 60. About 50 per cent of the sand used passed the 65-mesh sieve and about 10 per cent passed the 200-mesh sieve.

HEIGHT GAGE

Fig. 2--Instrument box

Fig. 3--Model of Alamitos Bay

Fig. 4--Model of Alamitos Bay--showing photographing cage on traveler

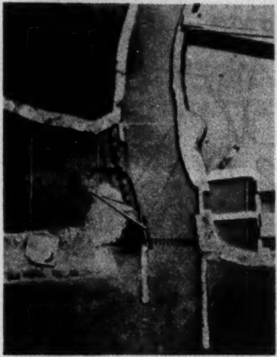


Fig. 5--Picture of model showing contour

(2) Tides--Tides were run by adding and withdrawing water at the Ocean intake. To produce a flood-tide, water was fed in at predetermined rates, which are calculated from the actual tide-curve, until high tide was reached. Water was then withdrawn through the discharge-meters until low tide was reached. The rate of rise and fall of the tide varies continually so it is necessary to vary the rate of flow of the water accordingly. Only the fact that any rate of flow can be obtained accurately and quickly with the venturi meters made this method of producing tides possible.

(3) Waves--Model ocean-waves were produced at the rate of 30 per minute by a motor-operated paddle. They were about three-fourths inch high from trough to crest and had an amplitude of from three to four feet. Their appearance as well as their action upon the sand was very similar to that of actual waves.

(4) River-flood--A river-flood was reproduced by supplying water at the east intake (source of river) and letting it out at the Ocean intake. Sand was added to the River near its source so that the water was laden to capacity when it entered the model.

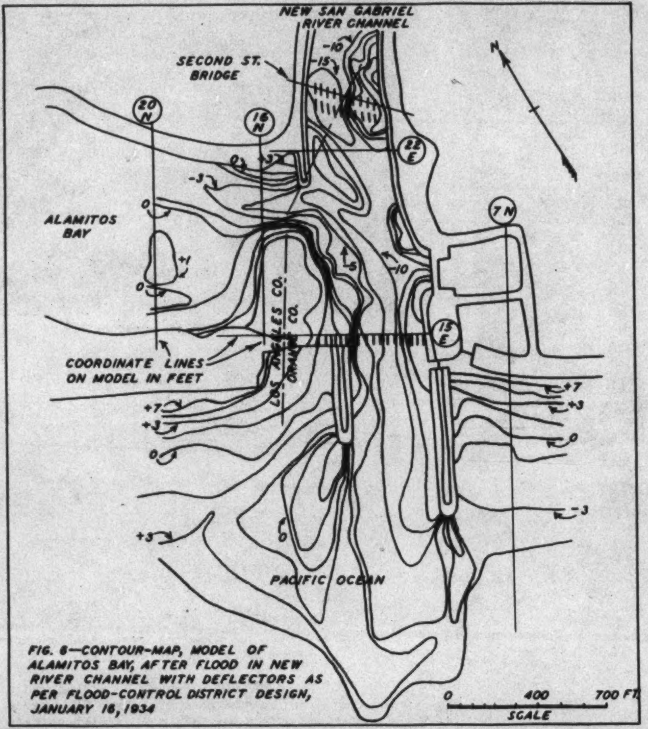

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
-10
-15
20 N
16 N
22 E
7 N
15 E
0
-3
-3
ALAMITOS BAY
+1
0
0
-5
-10
LOS ANGELES CO.
ORANGE CO.
COORDINATE LINES ON MODEL IN FEET
+7
+3
0
+3
0
+7
+3
0
-3
PACIFIC OCEAN
0 400 700 FT.
SCALE

FIG. 6—CONTOUR-MAP, MODEL OF ALAMITOS BAY, AFTER FLOOD IN NEW RIVER CHANNEL WITH DEFLECTORS AS PER FLOOD-CONTROL DISTRICT DESIGN, JANUARY 16, 1934

(5) Model-surveys--Practically all of the changes in the configuration of the model were recorded photographically. Figure 4 shows the cage over the model from which the photographs were taken. The cage is carried by the boom on the traveler and may be placed in any position over the model. The water in the model is brought to the level at which a contour is desired and a picture is taken. The shore-line in the picture gives the contour. Figure 5 shows a picture of a contour. The lines on the model serve to orient the pictures with one another. Each of the negatives of a survey is projected on a sheet of drawing-paper to the desired scale and the contour is traced upon the paper. The result is a contour-map. Figure 6 shows a finished contour-map.

When the light conditions were poor, the photographic method of surveying was not satisfactory and the surveys had to be made by hand. In the hand survey the contour was located by actual measurement and plotted on a sheet of paper much as is done in ordinary plane-table surveying.

(c) Experimental Results and Conclusions, by Robert T. Knapp

Acknowledgments--It is impossible to divide the responsibility for Parts (b) and (c) of this group of papers. Mr. Vanoni was working with the author constantly from the start of the design of the laboratory equipment to the conclusion of the study. What follows must be considered as much his work as that of the author. Also advantage must be taken of this opportunity to acknowledge the many helpful suggestions made by Colonel Charles T. Leeds, who gave freely of his wide experience with river and harbor problems to help make this study a success.

Review of model-problem--Figure 1 is a rough map of the territory involved in the problem. The area reproduced in the model is shown enclosed in the outline of the laboratory. The meandering course of the old river-channel is seen, entering the Bay at its midpoint. The location of the power-plant of the Los Angeles Gas and Electric Corporation is visible just to the east of the Inlet. The new flood-control channel is plainly shown at the right side of the Figure, entering the Bay just opposite the Inlet. It will be remembered that the purposes of this new channel were (a) to straighten the course of the River, decreasing its resistance and increasing its gradient to prevent flooding the low lands near the coast in times of high water, (b) to by-pass the Bay with the flood-waters of the River, so that in flood-periods the

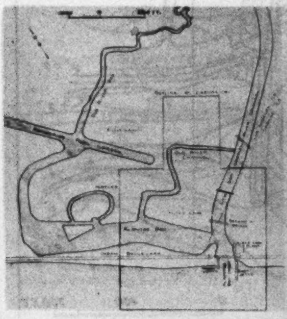


Fig. 1

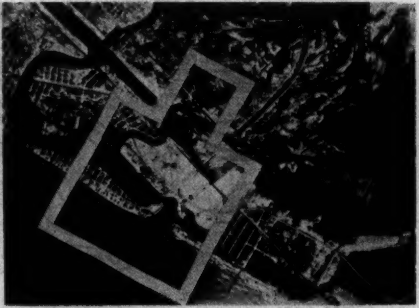


Fig. 2

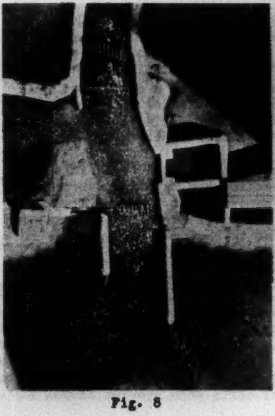


Fig. 8

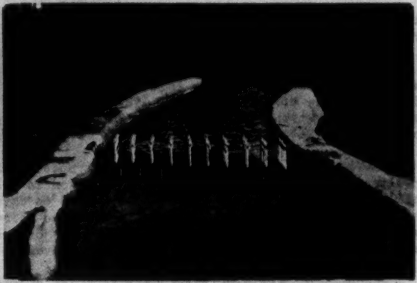


Fig. 9

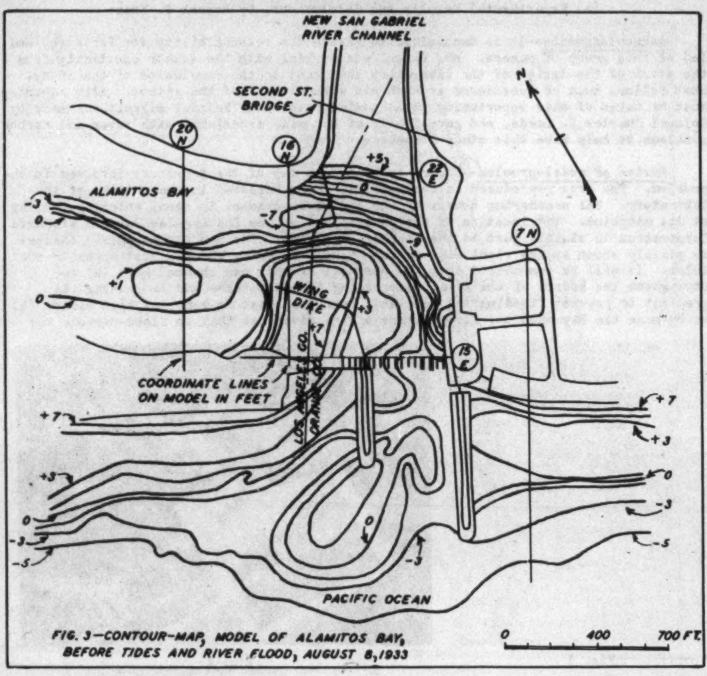

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
20 N
16 N
22 E
7 N
15 E
ALAMITOS BAY
+5
0
-3
0
-7
-9
+1
0
WING DIKE
+3
+7
LOS ANGELES CO.
ORANGE CO.
COORDINATE LINES ON MODEL IN FEET
+7
+3
0
-3
-5
+7
+3
0
-3
-5
0
-3
PACIFIC OCEAN
0
400
700 FT.

FIG. 3—CONTOUR-MAP, MODEL OF ALAMITOS BAY, BEFORE TIDES AND RIVER FLOOD, AUGUST 8, 1933

objectionable debris brought down would not be deposited in the Bay or on the property fronting on it.

One of the chief problems to be solved in making this channel-change was that of insuring the plant of the Los Angeles Gas and Electric Corporation a continuous and adequate supply of cooling water. This was a matter of so much importance to the Corporation that they agreed to furnish the major part of the funds necessary for this model-study. Naturally, therefore, this was the main objective of the model-study.

The sand-bar inside the Bay directly opposite the plant had much to do in controlling the position of the tidal channel and in protecting the Bay from debris. Thus the effect of the new river-construction on this sand-bar was likewise a point of great interest. The other points of importance whose study was pursued as far as time and funds would permit were the effect of the jetties on the beaches on each side of the Inlet and the investigation of the sand-movement caused by the waves.

Difficulties anticipated--A further study of Figure 1 will show that some troubles were to be anticipated. With the old river-channel in operation, the tidal channel followed the east jetty past the power-house and its cooling-water inlet, then made nearly a right-angled turn and swung into the Bay, with deep water mainly along the northeast shore. The water was shallow along the Bay sand-bar. The curvature of the flood-channel just as it enters the Bay, however, is in a direction to cause the flood-waters to swing the deep-water channel to the opposite side of the Inlet, thus

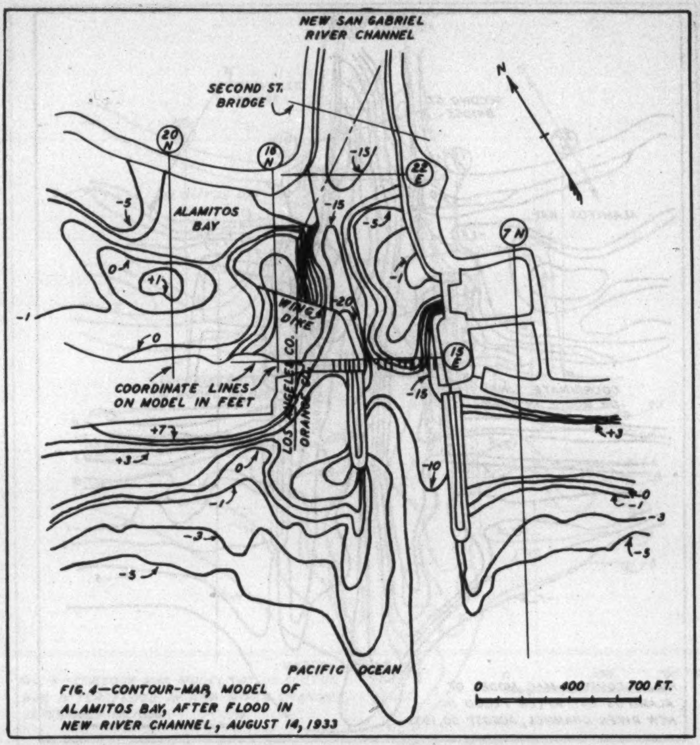

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
20 N
16 N
22 E
7 N
15 E
-15
-15
-5
-5
ALAMITOS BAY
0
+1
-1
-1
0
WING DIKE
-20
-15
COORDINATE LINES ON MODEL IN FEET
LOS ANGELES CO.
ORANGE CO.
+7
+3
+3
0
-10
-1
0
-1
-3
-3
-5
-5
PACIFIC OCEAN
0
400
700 FT.

FIG. 4—CONTOUR-MAP, MODEL OF ALAMITOS BAY, AFTER FLOOD IN NEW RIVER CHANNEL, AUGUST 14, 1933

having both the possibility of leaving the power-plant without sufficient cooling water and of scouring away the Bay sand-bar. This curve in the channel was made necessary by the available right of way, which could not be changed.

Another point of predicted trouble was thought to be the location and length of the jetties on each side of the Inlet. One of these was already constructed and the other one contracted for before the model-study was undertaken.

Figure 2 is an aerial photograph of the same territory with the area included in the model-study indicated clearly.

Check of validity of model-construction--Before the main studies were undertaken considerable time was spent in checking the model performance to see whether or not it was similar to its natural prototype. Fortunately, surveys were available of the underwater topography before and after the east jetty was constructed. The sand in the model was moulded to conform to the topography before the east jetty existed. The jetty was placed in position and a suitable series of tides, floods, and waves were run. Surveys of the model showed that the topography had shifted so as to correspond to the actual surveys made after the jetty was built at the beach. A repetition of

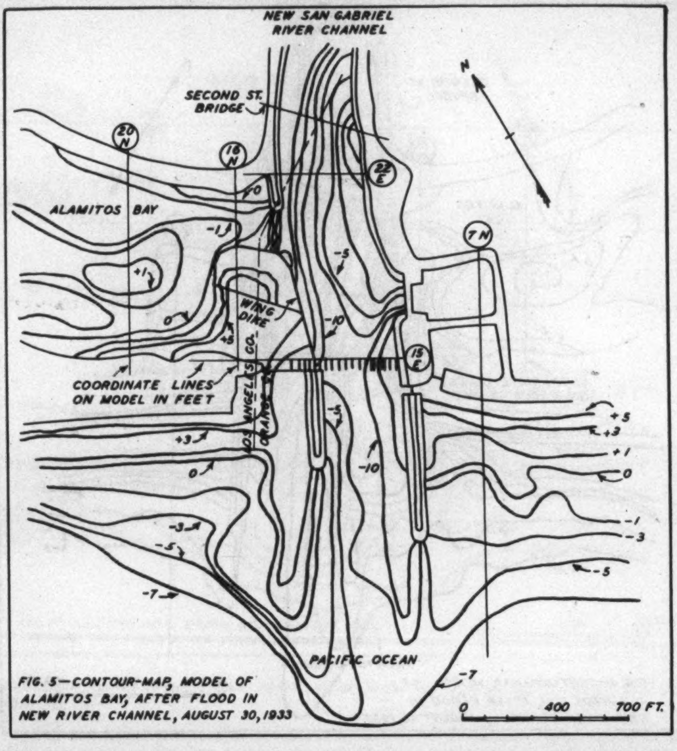

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
20 N
16 N
22 E
7 N
15 E
ALAMITOS BAY
WING DIKE
LOS ANGELES CO.
ORANGE CO.
COORDINATE LINES ON MODEL IN FEET
PACIFIC OCEAN
+5
+3
+1
0
-1
-3
-5
-7
-10
0 400 700 FT.

FIG. 5—CONTOUR-MAP, MODEL OF ALAMITOS BAY, AFTER FLOOD IN NEW RIVER CHANNEL, AUGUST 30, 1933

this check, together with many visual points of similarity seen during the model-operation served to show satisfactory correspondence between the behavior of the model and the prototype. It was felt, therefore, that it was justifiable to proceed with the use of the model in studying the effects of proposed changes in the river-channel.

Test of original solution of problem--At the time the study was undertaken the possible bad effects of the adverse curvature of the flood-control channel were fully realized. Tentative plans had been drawn up for protection works in the Bay. Figure 3 shows a map of the model with these works in place. They consisted of two wing-dykes, one beginning at the inner end of the west jetty and extending along the Bay sand-bar and into the Bay, and the other being a continuation of the west part of the river-channel, but also turning and extending into the Bay.

The topography of Figure 3 was that of the latest survey available and was used as the condition from which all the various experiments were started, that is, when a different construction was to be tried the model was remoulded to conform to Figure 3.

Starting with the model in the standard configuration but with the wing-dyke as originally proposed in place, a river-flood was run. The magnitude and duration of

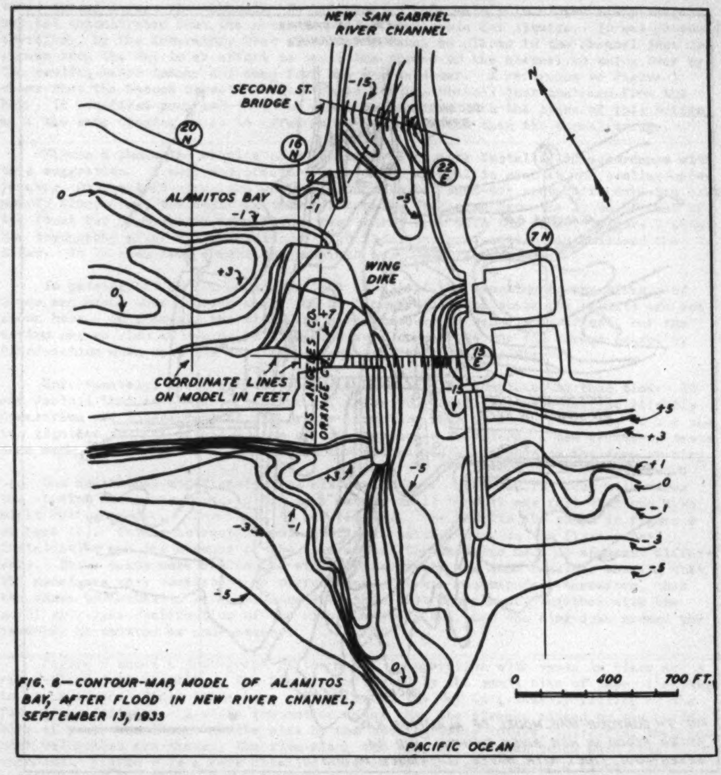

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
-15
20 N
16 N
22 E
0
ALAMITOS BAY
-1
-1
-5
7 N
WING DIKE
+3
0
+7
LOS ANGELES CO.
ORANGE CO.
15 E
COORDINATE LINES ON MODEL IN FEET
-15
+5
+3
+1
0
-1
-3
-5
+3
-1
-3
-5
-5
0
0
400
700 FT.
PACIFIC OCEAN

FIG. 6—CONTOUR-MAP, MODEL OF ALAMITOS BAY, AFTER FLOOD IN NEW RIVER CHANNEL, SEPTEMBER 13, 1933

the flood corresponded to the "design-flood" fixed by the engineers of the Los Angeles County Flood Control District. The results of this flood are seen in Figure 4. It will be noted that the deep-water channel has moved from the right-hand to the left-hand side of the Inlet. The cooling-water intake of the power-plant was nearly completely filled with sand. Severe cutting took place along the wing-dykes. It was concluded, therefore, that this tentative design would not be satisfactory.

First laboratory modification of design--A study of Figure 4 seemed to indicate that the wing-dyke around the Bay sand-bar did not extend far enough upstream toward the new channel and that the upper wing-dyke was too long. Therefore, the latter was replaced by a short spur-dyke and the former was extended to take in considerably more of the Bay sand-bar. The model was remoulded to standard conditions and a new flood was run. The results are seen in Figure 5, together with the modified construction, and are still very unsatisfactory. The entrance from the channel into the Bay was somewhat better, but the cooling-water intake was again sanded up and the scouring along the wing-dyke remained very severe.

Analysis of fundamental difficulty--A consideration of the two preceding runs

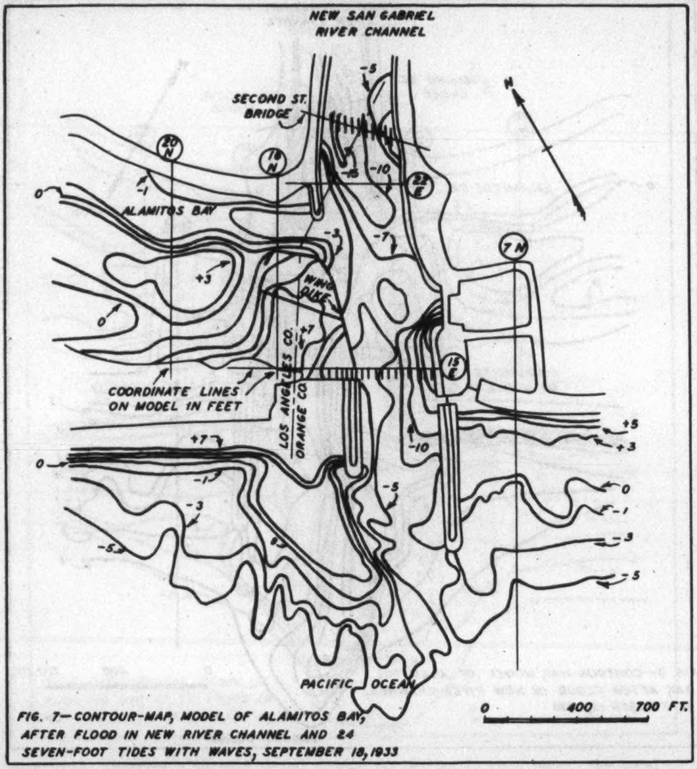

NEW SAN GABRIEL RIVER CHANNEL
SECOND ST. BRIDGE
N
20 N
16 N
22 E
7 N
15 E
-5
-15
-10
-7
-3
-1
0
ALAMITOS BAY
+3
0
WING DIKE
+7
LOS ANGELES CO.
ORANGE CO.
COORDINATE LINES ON MODEL IN FEET
+7
0
-1
-3
-5
-10
-5
+5
+3
0
-1
-3
-5
PACIFIC OCEAN
0
400
700 FT.

FIG. 7—CONTOUR-MAP, MODEL OF ALAMITOS BAY, AFTER FLOOD IN NEW RIVER CHANNEL AND 24 SEVEN-FOOT TIDES WITH WAVES, SEPTEMBER 18, 1933

showed that no progress was being made. The trouble was obviously due to the bend in the channel and the dykes proposed were unable to correct for the bad effects resulting from it. Further analysis led to the conclusion that the reason for this lack of success was that the room available for training works was insufficient to cause any effect before the sand-bar and cooling-water intake were passed. It was seen that the flood-waters must be directed toward the cooling-water intake and away from the Bay sand-bar before the water entered the Bay and not during its passage across the end of the Bay. It was also seen that it was very difficult to apply enough force to one bank of a wide and comparatively shallow stream to change the momentum of the entire stream in a limited space. However, the available right of way did not permit of changing the channel-direction upstream from the Bay. The problem, therefore, resolved itself into a search for some method of training the stream other than by working from the bank.

Solution proposed by Laboratory--Some time ago Professor Prandtl of Goettingen, Germany, developed a method of producing a sudden change in the direction of a stream of fluid which was very efficient. This was by the use of a series or lattice of vanes spaced across the channel. He had applied this mainly to closed air-passages but had demonstrated that the method was also applicable for liquids. It was proposed, therefore, by the Laboratory that a series of vanes be placed in the channel just upstream from the Bay in an effort to cause the thread of the channel to swing over by the cooling-water intake and away from the Bay sand-bar. A reference to Figure 1 shows that the Second Street Bridge crosses the new channel just upstream from the Bay. It was first proposed that the vanes be combined with the piers of this bridge, with the same spacing so as to offer no more obstruction than the normal bridge.

Figure 6 shows the results of a run made with vanes installed in accordance with this suggestion. A very satisfactory deep-water channel is seen at the cooling-water intake. On the left side, the cutting along the Bay sand-bar protective dyke has been nearly eliminated, the depth at this point being decreased from the 12 to 15 feet of the first two experiments down to not over three feet with the vanes. Figure 7 shows the topography after a long series of high tides and wave-action had followed the flood. It is seen that conditions remained very satisfactory.

In passing, it should be stated that in all of the experiments the effects of tides and waves were ascertained. Due to lack of time and space the results are not shown here. In general, the tides and waves produced a beneficial effect, but the action was so slow as not to be tolerable as a corrective for the damage caused by flood-action when only the wing-dykes were used to train the River.

Unfortunately, the Second Street Bridge was nearly completed at this time. It was decided that it would be simpler and safer to install the vane-lattice slightly downstream and independent of the bridge-structure than it would be to try to tie the two together so late in the course of construction. Therefore, a new series of tests were made with the vanes separate from the bridge-piers but keeping the same spacing.

One additional modification was also tried out. In the first test with vanes the cutting along the Bay sand-bar dyke was so small that it was felt that the dyke might not be needed. Therefore, it was removed. The results are shown in Figure 6 of Part (b). This construction was equally as satisfactory as the first vane-installation and the absence of the dyke around the sand-bar made no apparent difference. These tests were duplicated with substantially the same results, showing that the model was very consistent in performance. It was recommended, therefore, that the vanes be installed in accordance with this last experiment, together with the small spur-dyke continuation of the river-channel, but that the wing-dyke around the sand-bar be omitted as unnecessary.

Figure 8 shows a photograph of the model in operation with vanes in place and a river-flood just starting. The flow is indicated by the small bits of paper floating on the surface. Since there is a rising flood, the Bay is gradually filling as the flow-lines indicate. A close inspection shows that the streaks caused by the moving bits of paper are longer on the side by the cooling-water intake, indicating that the high velocities are there. The flow along the sand-bar is seen to be much less vigorous. Figure 9 is a more detailed picture of the vanes during a flood. The smoothness of the flow and the lack of disturbance due to the vanes should be noted.

Action along beach--Space permits only a brief mention of other interesting aspects of the problem. The action along the beach was very significant. Figure 3 shows the beach topography before the west jetty was constructed. The subsequent Figures show the rapid building up of the beach caused by the action of the tide and waves after this jetty was built. This agreed closely with the results observed on the prototype. An equally good agreement showed very little accretion on the beach east of the east jetty. This supported the contention of Colonel Leeds and others that the east jetty was too long and that further extension would lead to no useful result. It is regretted that time does not allow a further discussion of these interesting effects.

Suggestions for future studies--An analysis of the results as a whole leads to a sad conclusion. If the model-study could have been completed before the right of way had been obtained, it is nearly certain that all of the difficulties could have been avoided by a minor change in the location of the new channel. Even if the location of the channel had been fixed, the problem would have been solved more easily and more cheaply if the vanes could have been used as the bridge-piers. A plea is made, therefore, that model-studies be carried on well in advance of the beginning of construction in order that their full benefits may be realized.

Summary--It is felt that this study has justified itself in at least two ways. It has prevented the construction of training works that would have surely proven unsatisfactory and it has offered an alternative solution that appears to have a good chance of being successful and is certainly more sound fundamentally from the point of view of hydrodynamics. At the same time the savings due to the decrease in cost of the recommended construction over that originally contemplated should be much more than the cost of the model-study.

There are undoubtedly many hydraulic problems for which this double justification for a model-study is present, and, therefore, it is believed that both factors of safety and economy will urge that hydraulic model-studies be employed as a matter of regular procedure in the solution of all but the most straightforward of problems in hydraulic structures.

Future of the Laboratory--Now that this problem has been completed, at least as far as the major points are concerned, this Laboratory at the California Institute of Technology has commenced a similar study of the Ballona Creek Outlet, which is also a part of the drainage-system of the Los Angeles County Flood Control District. It is hoped that at some future time it will be possible to report the results of these experiments to those who are interested in them.

(d) Practical Application of Laboratory Results, by Charles T. Leeds

In the model-studies it was shown that the purposes desired could best be attained by constructing a series of curved deflector vanes in the river-channel downstream from the Second Street Bridge and by extending the west levee a short distance southerly as a wing-dike on the north shore of the mouth of Alamitos Bay. With these measures, and a bulkhead connecting the shore end of the west jetty with the west abutment of the Ocean Avenue Bridge, it was indicated that no further measures would be required except raising a portion of the inner bar somewhat above highest flood-level to prevent erosion of this marine park-area by overtopping.

While the model-tests were in progress, construction was begun on such units of the project as were of unquestioned merit and which could be financed, for the only funds available were allotments from annual tax levies. The first construction was 600 feet of the east jetty, rip-rapping the east bank therefrom to the Second Street Bridge, and additional steel sheet-pile and rip-rap protection at the power-plant.

To satisfy local demands, the east jetty was shortly extended 250 feet further seaward, without referring the matter for engineering advice.

When funds became available for the west jetty, this structure, on the author's advice, was built only as far seaward as mean lower low-water, thus limiting its length to 400 feet from the Ocean Avenue Bridge. To prevent cutting around the shore-end, a creosoted sheet-pile bulkhead was constructed along the southerly line of the Bridge, connecting its westerly abutment with the jetty, instead of constructing the expensive rock-levee northward from the Bridge, as previously proposed by the District. As anticipated, and as in the model, the sand-accretion west of the jetty was rapid, practically keeping pace with the jetty construction and filling to the top of the bulkhead.

Since funds were inadequate to excavate the flood-channel north of Second Street Bridge to full cross-section with complete bank protection, it was deemed wise as a safety measure to excavate a minor central channel with temporary bank protection, thus affording direct outlet for minor floods. This did occur last winter, with no damage.

Meantime the model-tests had been completed and the conclusions and recommendations therefrom were approved by both the District and the power-corporation. Detailed plans for the deflector-vanes and spur-dike were prepared and construction of same is now under way.

The deflector-vanes are designed as cantilevers, relying for stability on ground-penetration, rather than having less penetration and supporting the tops by interconnection and ties or struts to the river bank. Each deflector-vane consists of a series of steel King piles, of H-section, tapered toward the top, driven to a depth of -55.0 feet, with pre-fabricated creosoted-wood panels between, extending down to -14.0 feet. Below this grade, to assure against underscour, steel-sheet piling is to be driven. Care was taken in the design to secure as smooth a surface as possible on the convex side of each vane, confining any necessary irregularities to the concave side.

The probable depth of scour and the effective size and thickness of rip-rap protection to be provided were items in which the results of the model-tests were qualitative rather than quantitative. The model showed, of course, a definite depth of scour under definite flow-conditions, but it must be borne in mind that the model was perforce constructed at distorted scale, and the sand available for use was not proportionally similar, either in effective size or in specific gravity. Nevertheless, it is believed that the results of the model-tests, when interpreted with judgment, made possible a better and more reliable solution of the problem than would have been the case by other means.

In conclusion, it should be noted that the model-tests clearly indicated the best solution of this complicated problem and made it possible to design the necessary control-works with far greater certainty of results than would have been possible by any mathematical calculation. Not only was this true, but the economy effected by the improved design made possible a saving of many times the cost of the experiments with the model.

The tests were not carried as far as desired toward determining the best design of jetties at the mouth of the Inlet and the effect on littoral drift. Such conclusions as could be drawn from the tests, however, were entirely corroborated in the prototype. Both the model and the prototype have clearly shown the advantage, in beach-building, of keeping the jetties short, and also the futility as well as the undesirability of lengthening the east jetty as was done. This action takes place not only in time of flood but continually under the influence of tidal and wave-forces.

Due to the urgency of the flood-problem on Ballona Creek, it was necessary to terminate the study of the San Gabriel River mouth and prepare to make similar model-tests of the mouth of Ballona Creek. The latter problem, though similar, is more complex and difficult. It is hoped by these new tests to afford further light on the problems of beach-erosion and accretion at stream-mouths on a sandy coast, which may be of interest and value.

Appreciation should be expressed to the Board of Supervisors and to E. C. Eaton, Chief Engineer of the Los Angeles County Flood Control District, for their broad vision in adopting this method of investigation, and to the Los Angeles Gas and Electric Corporation and to H. A. Masser, Executive Engineer thereof, for their generosity in so largely financing these tests. These tests have unquestionably saved many times their cost and have demonstrated the advantage of solving similar problems by use of an hydraulic model.

Quinton, Code and Hill - Leeds and Barnard, Engineers Consolidated (C.T.L.),
Los Angeles, California, and
California Institute of Technology (V.A.V. and R.T.K.),
Pasadena, California

THE TRANSPORTATION OF BED-LOAD BY STREAMS

Morrough P. O'Brien and Bruce D. Rindlaub

The problem of bed-load movement has been studied by a number of engineers and scientists during the past seventy years and a considerable amount of data has been published. The increasing use of river- and harbor-models has accentuated its importance because of the necessity for selecting a material capable of being moved which will not at the same time form excessively large ripples. The present paper is the result of a critical survey of available data made to ascertain whether or not a quantitative prediction of bed-movement is now possible.

Tractive force--The theory of du Boys relates bed-movement to tractive force, and this conception appears to be sound. Regardless of the exact manner in which this tangential force is applied to the bottom, there can be no question of its existence, because such a force is necessary if mechanical energy is to be dissipated in friction. Considering any open channel, the total force per unit-length is

$$w A s \tag{1}$$

where w is the unit-weight of water, A is the cross-sectional area, and s is the slope of the energy-gradient. This tractive force is distributed over the wetted perimeter and its average value per unit-area is

$$T = w A s/p = w R s \tag{2}$$

where p is the wetted perimeter, and R is the hydraulic radius.

It is evident from the velocity-gradients at the boundaries of channels that this force is not uniformly distributed as assumed. Methods of estimating the distribution of tractive force from the velocity-distribution have been proposed but unfortunately they cannot be applied to the data on bed-movement because experimenters have not included velocity-traverses in their measurements. In this study the average tractive force on the sides and bottom has been used. This procedure probably gives a value which is slightly lower than the actual force acting on the bottom and greater than that at the sides in the usual experimental channel.

Most of the experimental results on the relation between tractive force and bed-movement involve two fundamental errors, namely, depth is used in place of the hydraulic radius and slope of the water-surface in place of that of the energy-gradient. For usual ratios of width to depth, the first error gives shearing forces which are from 5 to 20 per cent too high. The second error is very important and probably accounts for much of the scattering results obtained in the laboratory in short channels where the slopes of water-surface, of bottom, and of energy-gradient may differ materially. It is to be noted that the slope of the bottom is more nearly equal to the slope of the energy-gradient than is the slope of the water-surface and partly for this reason, the data of G. K. Gilbert show less scattering than the data of more recent experimenters who have criticized Gilbert for not measuring the slope of the water-surface in all of his experiments (see Fig. 1).

Accurate determination of the slope of the energy-gradient requires measurement of the distribution of velocity at each end of the experimental reach. Without velocity-distributions, the velocity-head can be computed only approximately and the error involved becomes large for usual experimental conditions.

In many cases, the slope must be computed using one of the friction-equations and it is convenient to substitute for the slope in equation (2). Adopting the Manning equation, which fits the experimental results on large and small channels as well as that of Kutter and has the advantage of a more reasonable form

$$S = nv^2/(1.49)^2\ R^{4/3} \tag{3}$$

$$T = w\ n^2v^2/2.22\ R^{1/3} \tag{4}$$

Friction-factor and size of material--The first step in using equation (4) is to select a proper value of the friction-coefficient, n. This is difficult for channels with fixed boundaries and is doubly so when bed-movement is involved. The effective roughness of the bed may be fixed by the size of ripples left by some preceding flow and be independent of the size of particles forming the bottom. However, experiments on artificially-roughened flat plates show that n increases with the size of the rugosities and there is reason to believe that the size of ripples depends, in part at least, upon the size of the bed-material.

From a consideration of the dimensions of the quantities involved, Manning's

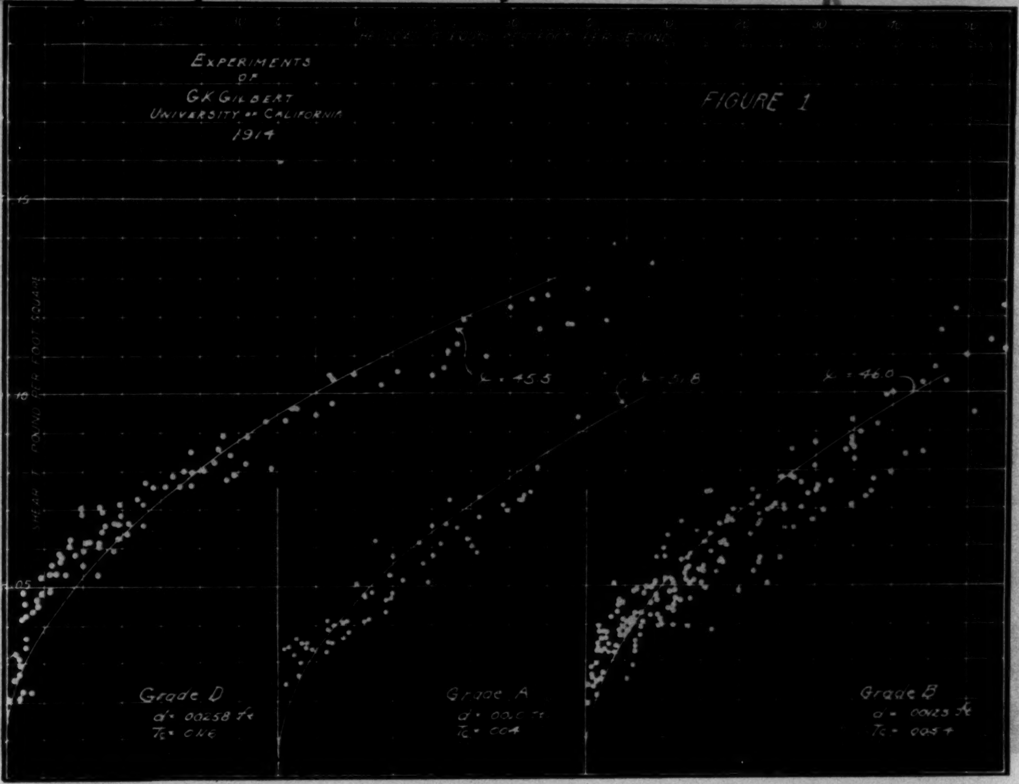
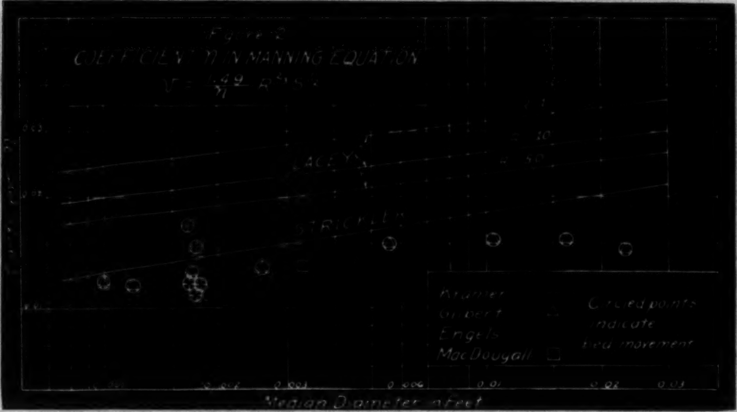


FIGURE 1

EXPERIMENTS
OF
G K GILBERT
UNIVERSITY OF CALIFORNIA
1914
PER FOOT PER SECOND
SHEAR T POUND PER FOOT SQUARE
.15
.10
.05
10
20
30
40
50
k = 45.5
k = 51.8
k = 46.0
Grade D
d = .00258 ft
Tc = .016
Grade A
d = .00[illegible] ft
Tc = .004
Grade B
d = .00123 ft
Tc = .0054



equation is dimensionally sound only on condition that the friction does not depend upon the viscosity (fully-developed turbulence) and the factor n has the dimensions of $(\text{length})^{1/6}$. Strickler (Mitt. des Amtes für Wasserwirtschaft, Berne, 1923) has proposed the equation

$$n = 0.039\ d^{1/6} \tag{5}$$

where d is the median diameter of the surface-layer in feet. Unfortunately, most of the measurements of n for natural channels have not been accompanied by an analysis of the bed-material and the only data available for checking this relationship were obtained in small laboratory channels. Figure 2 shows the equations of Strickler and Lacey together with the experimental results. The data of Engels were computed using equation (4) from tractive forces measured by means of a delicate balance. The values of n are somewhat lower than are found for natural channels. The points for zero bed-movement agree reasonably well with those for fully developed movement.

Schoklitsch (Über Schleppkraft und Geschiebebewegung, Engelmann, 1914) concludes from his own experimental data that the frictional resistance increases with increase of bed-movement but his method of computing the resistance of the bed appears to be unsound. Most of the experimental data show that, starting with an initially smooth bed, the friction-factor increases abruptly as bed-movement starts and then decreases, approaching the initial value asymptotically. The explanation of this may be that as bed-movement starts, part of the surface-layer is torn loose and moves along slowly over the remainder of the surface-layer, thus increasing the roughness. As the tractive force increases, a point is reached at which the whole surface-layer is in motion and the roughness of the stationary surface is approximately the same as in the initial state. This explanation is rather idealized but the experimental data indicate that some similar phenomenon occurs in natural mixtures.

Another important feature of the relationship between friction-factor and size of material is the effect of the sequence of measurements. In a series of runs in which the tractive force is increased to the point of ripple-formation and then decreased below that which will start motion, the disturbed bed should show a higher value of n than in the original condition. This result is indicated by Kramer's experiments (Proc. Amer. Soc. C. E., April 1934). He did not measure the rate of bed-movement and the comparison in Table 1 is on the basis of conditions which appeared to give the same movement. The experimental results were:

Table 1

Sand	Median diameter	Values of n	
		Initial	Final
	feet		
I	0.00174	0.0108	0.0145
II	0.00168	0.0101 0.0110 0.0102	0.0157 0.0169 0.0176
III	0.00180	0.0104	0.0118

These results indicate that the roughness-coefficient does not depend upon the size alone and that the sequence of events must be considered in estimating the proper value to be used.

Critical tractive force--The experiments of Engels on the tractive force on flat plates flush with the walls of a channel have been mentioned previously. Another set of experiments which point to the importance of tractive force in bed-movement are those of Chitty Ho (unpublished thesis for the Doctor's Degree, State University of Iowa, 1933) in which materials of different sizes were placed in a recessed chamber with the upper surface flush with the bottom of the channel proper. Using different depths, the velocity was increased until the material started to move, at which condition the velocity-gradient along the center line of the channel was measured. The important feature of the results is that for each material the velocity-gradient near the bottom necessary to start movement was a constant, regardless of the magnitude of the average velocity and depth. It is known that the velocity-gradient near a solid boundary depends upon the shearing force and the conclusion to be drawn from these experiments is that the shearing or tractive force is the important variable and that it must exceed a definite value, if movement is to occur.

Several attempts have been made to find an equation which will give the tractive force necessary to start movement. The authors have compared the equations of Schoklitsch and Kramer with experimental results on 39 different sands and have come to the conclusion that the best correlation of existing data is obtained by simply plotting median diameter against critical tractive force. Figure 3 shows the experimental results on material mixtures and fractions segregated by screening together with the equation of Krey

$$T_c = (4.6 \text{ to } 7.2)d \qquad (6)$$

where T_c is the critical tractive force in pounds per square foot and d is the median diameter in feet (50 per cent on sieve-analysis). Neglecting the data of Schaffernak, for which the tractive force has been computed by means of equation (4), the upper limit of Krey's equation gives a force which will move nearly any natural material. Even the lower limit is conservative and the equation of this type which would best fit all of the data is approximately

$$T_c = 3.5\ d \qquad (7)$$

Scattering of the experimental points resulting from differences in experimental technique, errors in observation, and mistakes in computing the tractive force are such as to make an elaborate analysis of the data unwarranted.

Throughout this discussion it is assumed that the slope of the bottom is small as compared with the angle of repose of the material.

Rate of bed-movement--The term bed-load has not been defined previously because the conception of tractive force is necessary to the definition. As used here, the term bed-load refers to that portion of the material carried by a stream or channel in such a manner as to be caught in a trap of reasonable length and proper design. As the tractive force is increased above the critical value, the first stage of the phenomenon is bed-movement. Further increases in tractive force increase the height to

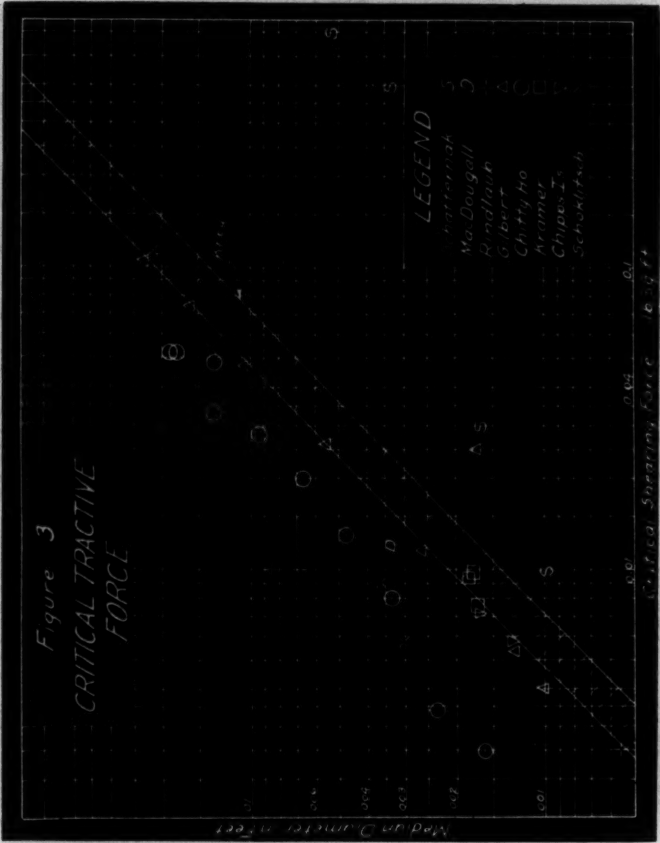
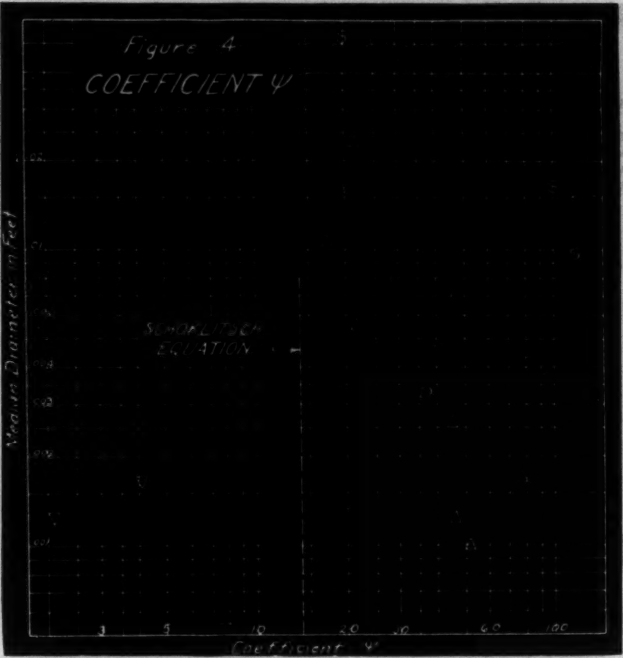


Figure 3

CRITICAL TRACTIVE FORCE

which particles are carried by the turbulence and finally a state of suspension is reached. Whether accompanied by suspension or not, the material moving near the bed is considered as bed-load. In nearly all of the experiments considered here the tractive force was not sufficient to throw the material into suspension. Bed-load movement is believed to merge gradually into suspension without any clear line of demarcation, and differentiation between them must be made arbitrarily. The definition stated here makes the amount of bed-movement depend upon the size and type of sand-trap used in an experimental study. A very large stilling-basin would trap both bed-load and suspended material while a short trap would fail to hold even the material moving by saltation in low, short trajectories. This experimental difficulty probably accounts for some of the variations in the measured results.



The equation of du Boys for the rate of bed-movement is

$$G = \psi T(T - T_o) \tag{8}$$

where G is the rate of movement, measured here as pounds per foot of width per second and ψ is a coefficient. This equation was derived on the unsound assumption that the tractive force is dissipated in the bed. Schoklitsch found, however, that it fitted his data and proposed as the equation for homogeneous materials

$$\psi = 8.67\ w/(w_1 - w) \quad \text{in cubic feet per pound-second} \tag{9}$$

where w_1 is the weight of the material per unit-volume, and w is the weight of water. For quartz sand in water, $\psi = 13.9$. Figure 4 gives values of ψ for a number of sands as a function of the median diameter. There is a tendency towards an increase in ψ as the median diameter increases but the scattering of the points does not justify a detailed investigation.

Errors in the determination of T_o are reflected in the corresponding values of ψ and more accurate data will be necessary to establish a general relationship for these constants.

Figures 3 and 4 indicated a variation in the constants ψ and T_o with size of material and this fact raises a question as to whether or not a mixture should be treated as a unit. If we assume that each constituent in a mixture moves independently, then the total movement could be represented by an equation

$$G = P_1f_1(T) + P_2f_2(T) + \cdot \cdot \cdot P_nf_n(T) \tag{10}$$

where $f(T)$ represents the rate of movement of each fraction under the action of the tractive force T and P is the percentage present.

The only experiments on mixtures of which each constituent had been tested separately, appear to be those of Gilbert on his sands C and E. In Table 2 are shown the rates of movement computed from equation (10) and those measured by Gilbert. The deviations are no greater than from the curves of $f(T)$ for the two components.

Table 2

Mixture-percentage		Rate of movement	
C	E	Computed	Measured
48	58	0.0561	0.0620
		0.0787	0.0884
		0.1037	0.0905
		0.1100	0.1100
		0.1312	0.1150
		0.0684	0.0884
		0.0676	0.0905
Sub-totals		0.6248	0.6448
31	69	0.0570	0.0575
		0.0961	0.0861
		0.1296	0.1260
Sub-totals		0.2827	0.2696
19	81	0.0616	0.0618
		0.0937	0.0884
		0.1149	0.0927
		0.1363	0.1120
		0.1630	0.1190
Sub-totals		0.5695	0.4739
Grand totals		1.477	1.388

Consideration of the actual structure of a mixture in which the smaller grains partially fill the voids between the larger ones makes the assumption that each constituent moves independently appear unreasonable. However, it has the virtue of simplicity and agrees reasonably well with the data available.

The du Boys equation is based on the assumption that the shearing force parallel to the bed decreases with distance downward, a condition which would result in continuous acceleration. In a state of dynamic equilibrium, the shearing force must be constant on planes parallel to the bottom. An assumption which appears to be more reasonable than that of du Boys is that the frictional resistance increases.

Considering the material which remains at the bed and assuming that sand has a static friction which depends upon the weight of material above any layer, the movement may be treated in the same way as for the so-called "Bingham substance." The velocity-gradient in the bed is

$$(du/dz) = -M(T - t) \tag{11}$$

where the coefficient M is termed the mobility. Because of closer packing of the sand-grains with pressure, the increase in static friction is probably not directly proportional to the depth, Z, below the sand-surface. Assume that the static friction is

$$t = T + N\,Z^a \tag{12}$$

where T_o is the critical tractive force as previously defined and N and a are constants. At some point in the bed the static friction will be equal to the tractive force and below this point no motion will occur. The conditions here are

$$(du/dz) = 0, \quad Z_o = [(T - T_o)/n]^{1/a} \tag{13}$$

Substituting equation (12) in equation (11) and integrating gives

$$u = -M\,(T - T_o)\,Z + MN/(a + 1)\,Z^{a+1} + \text{const.} \tag{14}$$

at $Z = Z_o$, $u = 0$, and equation (14) becomes

$$u = M\,(T - T_c)\,(Z_o - Z) - MN/(a + 1)\,(Z_o^{a+1} - Z^{a+1}) \tag{15}$$

The weight of sand moved is

$$G = w_1 \int_o^{Z_o} u\,dZ = w_1 aM/[(2a + 4)N^{2/a}\,(T - T_o)^{(a+2)/a} \tag{16}$$

If a = 1, corresponding to a linear increase in f

$$G = (w_1 M/6N^2)\,(T - T_o)^3 \tag{17}$$

Simplifying equation (16) to

$$G = K_1(T - T_o)^b \tag{18}$$

Analysis of Gilbert's data for his sands A and C gives the results shown in Table 3.

Table 3

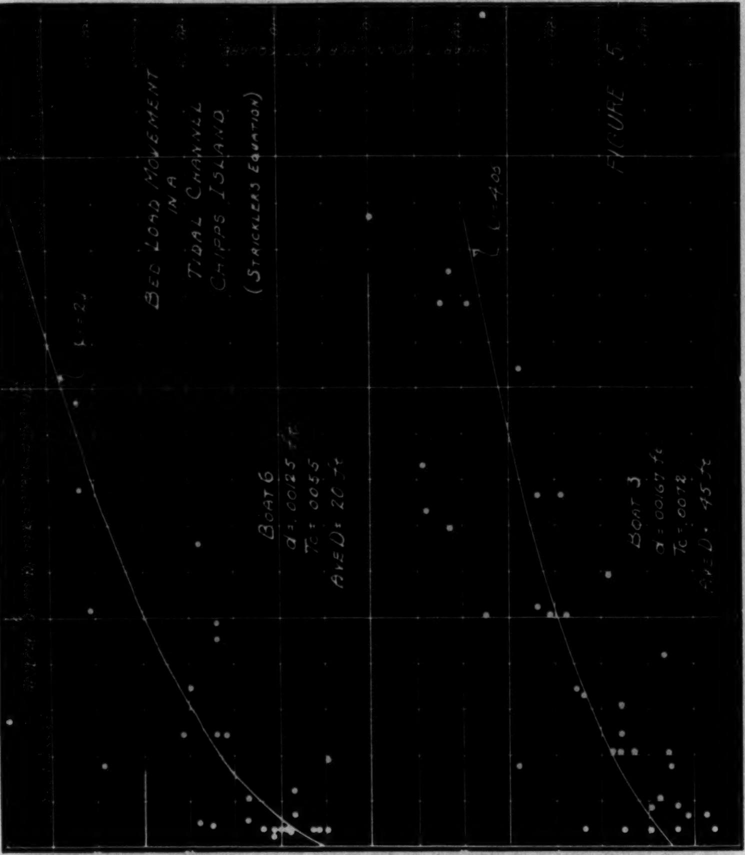
Sand	Median diameter	K_1	b	a
	foot			
A	0.0010	0.116	1.3	6.7
C	0.0017	0.105	1.4	5.0

In the ideal case of horizontal layers of uniform material, the relation between G and T should show discontinuities as successive layers are set in motion. This phenomenon may account, in part, for the scattering of the experimental data on fractions of natural sands such as Gilbert used. Another factor in the scattering of the experimental data is the fact that the static friction depends upon the arrangement of the particles and may vary through a range of equally probable values in a random mixture.

Equations (16) and (18) may prove to be no more suitable than the equation of du Boys for the representation of experimental data but they possess the advantage of being derived from reasonable assumptions.

Bed-movement in natural channels--The nature of bed-movement is such as to render field-measurements difficult but the desirability of checking results in the laboratory, at least approximately, is evident. The only field-measurements which have been found were made in the Straits of Carquinez by the United States Engineers. Tidal currents prevail at this point and the shearing force was estimated on the basis of equation (4) using the average of the squares of the velocities at beginning and end of the collection-period. Figure 5 shows the observations. One interesting feature is that the critical tractive force falls in the range established by experiments in small channels. The value of ψ is open to question but, as given, is lower than would be expected from the size of the material.

Conclusions--From a survey of most of the published data on bed-movement, it is concluded that none of the equations for critical tractive force or rate of bed-movement is sufficiently reliable to be used for design. For estimating these quantities approximately, the equations of Krey and Schoklitsch appear to be satisfactory but should be used with caution because considerable deviations from them have been observed.



Before the conception of bed-movement as a function of tractive force will be accepted generally, measurements in natural channels will be necessary and these observations should be accompanied by studies in thelaboratory of the same material. The basic theory appears to be sound but the experimental data should cover a wider range of depth, velocity, median diameter, and distribution of sizes.

The present status of the bed-load problem is analogous to the situation in the design of concrete structures, in which numerous tests are made to determine strength. In the absence of a quantitative theory relating the rate of movement to the specific gravity and distribution of sizes, each bed-material must be tested but this necessity does not invalidate the theory of tractive force as the controlling factor.

Correlation of data on bed-movement has usually been based upon a characteristic size and variation in size of a mixture. Schoklitsch has considered shape but determined the shape-factor from his measurements of bed-movement, thus making it really a correction-factor which takes into account other factors as well as shape. The conception of tractive force as the independent variable points to hydraulic resistance as the characteristic to be studied and suggests that the velocity of fall in a suitable liquid may provide a basis for correlation.

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THE REMOVAL OF BED-LOAD FROM ARTIFICIAL CHANNELS

R. L. Parshall

Disturbance by man of nature's balance has, in many cases, resulted in excessive soil-erosion, which is now looked upon with much concern. The eroded material, carried into the main streams by their tributaries, constitutes a major problem for the engineer in endeavoring to rid irrigation, power, and municipal water-supplies of sand and silt deposited in the diversion-channels.

The annual expense incurred in the operation and maintenance of water-systems of various kinds carrying sand and silt amounts to many millions of dollars in costs of excavation and in loss of revenue from power or water, due to time required for sluicing.

Properly designed diversion-dams and suitably controlled and operated head-gates and sluiceway channels may greatly reduce the amount of the heavier materials taken in at the heads of the systems. In many places, however, where water is diverted from streams and used for irrigation the general practice is to tolerate the sand and silt in order to secure the water. In an attempt to reduce the cost of operating and maintaining such systems, attention is being given to the problem of developing practical devices that will materially reduce the amounts of sand and silt deposited in the canals.

During the past two years, the Division of Irrigation, in cooperation with the Colorado Agricultural Experiment Station, has been conducting studies at the Bellvue Hydraulic Laboratory near Fort Collins, Colorado, regarding various sand-trap devices in which the effect of cavitation in flowing water, an induced action resulting from the flow of a stream of water past or over a projecting edge, is the basic principle. Three distinct types of traps have been tested, namely, the vortex-tube, the riffle-deflector, and the grating-type. Laboratory-settings of these devices appear to indicate effectiveness in capturing the bed-load which moves downstream along the bottom of the channel. For the vortex-tube relatively high velocities are required for successful operation, while with the riffle-deflectors more or less moderate velocities, and with the gratings moderate to low velocities appear to be most effective.

The vortex-tube consists of a tube of special design laid across the bottom of the channel with the axis inclined upstream from the tube-outlet at an angle of about 45°. The downstream top side or quarter is removed, the upstream top edge of the tube forming a lip or projection over which the water flows. The negative pressure induced on the under side of this edge or lip by the flow of the main stream causes the water within the tube to be turned upward on that side and downward on the opposite side, due to the drop over or across the tube. These two forces being in a common rotative direction cause, under the optimum condition of flow, a true horizontal vortex in which, in clear flowing water, a core of appreciable diameter may be observed. A rather extensive series of observations have been made, which show that the angle of axis of tube to thread of stream passing over the tube is not materially important. The best or most efficient action appears to be for settings with angles ranging from 60° to 30°. Where the velocity of the water over the tube is greater than the critical, the action within the tube is optimum. For such conditions of flow the vortical action or spiraled flow is especially efficient in transporting sand and gravel. Tests to determine the carrying or transporting power with a 4-inch tube, set at 45° to axis of channel, have shown that cobblestones as large as golf balls are supported and rapidly conveyed within the vortex and ejected through the outlet-end of the tube. Observations also have been made with tubes six inches in diameter and approximately 30 feet long. With the long tubes a singular phenomenon has been noted in that sand fed uniformly into the tube will travel in nodes toward the outlet. The cause for this is not readily apparent. Three field-installations of this type of sand-trap have been made, and all have proven effective. Tests in the laboratory indicate that the vortex-tube type will remove from 75 to 90 per cent of the bed-load.

The riffle-deflector type of trap also is efficient in its action. This device consists of a series of curved vanes set on a smooth surface. The action of both wooden and sheet-metal vanes of various sizes and shapes have been studied. The best results have been obtained with curved metal vanes about 10 inches high, set in a straight line and spaced about 10 inches apart. In plan each vane is curved into approximately a 90° arc of a circle. When set in a line normal to the current and properly spaced, these vanes will move the bed-load directly across the stream to a suitable opening in the side wall of the channel. With the vanes completely submerged in the flowing stream two distinct actions are induced: First, the obstruction causes the current to turn upstream just behind the line of riffles; second, the curved surface of the vane causes a decided cross-flow. Thus the back-current holds the sand close in behind the riffles, while the cross-current moves the load laterally to the side of the channel. Not only is it possible to move the bed-load at right-angles to the direction of flow, but it has been demonstrated that, by giving the vanes the correct curvature and spacing in line, the bed-load has actually been moved upstream along a course at an angle of 135° to the direction of the current. With these settings considerable energy is developed, sufficient, in fact, to move large cobblestones readily along a path just downstream from the line of riffles. This action is independent of the draft through the outlet-opening. One field-installation of the riffle-deflector-type of trap has been made, and it was found to function efficiently provided the vanes could be kept rid of such debris as tin cans, paper cartons, and other trash. Tests made with this trap, which was placed in the Wannamaker ditch near Golden, Colorado, showed that the device diverted fine sand from the ditch at the rate of approximately 15 pounds each second. However, owing to the overabundance of debris carried in this small channel, which has a capacity of only about 30 second-feet, it was necessary to remove the vanes and convert the installation into a vortex-tube trap.

The grating-type of trap is relatively new. In brief, this device consists of a series of vanes, either straight or curved, set normal to the flow, uniformly spaced, and with the top edges turned downstream. Gratings made up both of straight and of curved vanes have been tested to a very limited extent in the laboratory, with models of relatively small dimensions. In these studies no great difference in the efficiency of the two forms has been noted, both appearing to give very satisfactory results. Vanes both of sheet metal and of wood also have been tried in the laboratory, apparently with equal success. The metal vanes used consisted of strips of galvanized sheet steel, three to four inches wide and 12 to 18 inches long, fashioned with various slopes and degrees of curvature of the top edge. For the vanes made of wood, common laths were used. These were nailed in place in a suitable frame, with the face of each lath inclined downstream at an angle of about 45° from the vertical and with all of the uppermost corners planed down to a common level.

The grating consists of a series of individual vanes, properly aligned and spaced and set in a suitable supporting frame. In the experiments made the gratings were 24 to 36 inches long and 12 to 18 inches wide, with the spacings between the vanes ranging from one to three inches. The vanes were set so that their top edges were level with the floor of the flume. By placing the frames end to end in the stream-channel any length of grating desired can be readily obtained. A hopper or catchment-basin is provided beneath the grating to catch the deposited material and to serve as a means of regulating the discharge downward between the vanes. Observations indicate that the efficiency of the device is not impaired by closing the outlet of the hopper. As with the vortex-tube and riffle-deflector types, its action seems to be independent of the effluent stream.

A considerable proportion of these preliminary studies was conducted in a small flume having a plate-glass side through which the action of sand-particles moving through the gratings could be noted. The vortical action on the downstream side of the top edge of the grating vane was very noticeable. The general theory of the action of this type of sand-trap is that the sand-particles are drawn down behind the top edge of the device and retained there so that, through the force of gravity, they may settle vertically downward into a suitable receptacle beneath the grating, whence they may be discharged back into the main stream. As yet, nothing is definitely known as to the relative dimensions, spacing, curvature, or depth of vanes, best suited to any particular type of sand or silt.

It is now believed that the grating-type of trap will prove to be efficient in catching not only material of large size, but also exceedingly fine particles approximating that passing a 200-mesh screen. Observations in which potassium permanganate coloring matter was permitted to approach the grating along the floor of the channel were made in the glass-sided flume referred to, and it was noted that the vanes arrested and retained this coloring matter. This dye has a specific gravity of about 2.7, which approximates quite closely that of the silt carried in Colorado River. The ability of the grating to capture the coloring matter seems to offer considerable promise of eliminating at least a fair proportion of such silt as is carried in most of our western streams.

Naturally, there arises a question as to the amount or percentage of the total supply of water that is used in operating the several types of sand-traps. The investigations thus far made indicate that the normal action of each of the three devices described is independent of the rate of outflow from the trap. In some of the tests 10 or 15 per cent of the total flow has been wasted, while in other instances less than one per cent has been sufficient. In general, it may be said that the amount of effluent water must be sufficient to carry off the trapped material.

There is now in operation on Alamo River in Imperial Valley, near El Centro, California, a laboratory constructed for the purpose of studying methods of removing fine sand and silt carried in that stream, under conditions essentially identical with those obtaining in Colorado River. This Laboratory was constructed by the Division of Irrigation with Public Works Administration funds, the Bureau of Reclamation cooperating in providing funds for operation. Two methods or types of sand-traps, the vortex-tube and the grating, are to be investigated.

The Alamo River Laboratory consists of a framed structure about 100 feet long, carrying a rectangular flume 10 feet wide and eight feet deep. This flume-section is carried on heavy framed bents with the floor of the channel eight feet above the foundation-base. Built beneath this flume, and suitably supported, is a hopper extending the full length of the structure. The water-supply for the Laboratory is diverted from Alamo River at a point just upstream from Rositas Dam and is delivered to the main flume-structure through an earthen channel some 600 feet long. The study of vortex-tubes covers flow through three 6-inch constant-diameter tubes, with the upstream tube set at 60°, the center tube at 45°, and the downstream tube at 30° to axis of channel. The lip of each tube is set level transversely across the channel, and all have the same elevation, and discharge through the side wall of the flume at the floor-line. At the outlet point of each tube, on the outside of the flume, a small compartment is provided for the purpose of receiving and regulating the flow from the tube. A vertical metal pipe through the bottom of this submergence-chamber carries the trapped sand-load from the tube and suitable sampling apparatus is provided to sample the jet-flow from the end of this vertical waste-pipe. The discharge from the vortex-tubes is determined by measuring the pressure-head on each of the jet-outlets. These jets have been calibrated by passing the discharge over a standard 90° notch weir.

The gratings to be installed are made up with vanes formed from strips of No. 26 gage galvanized sheet iron, six inches wide and 28 1/4 inches long. These vanes have the top edges turned downstream in an arc having a radius of about one inch, the lower portion of each vane being a vertical plane surface. Three different spacings between vanes, namely, 1 3/8, 1 7/8, and 2 1/2 inches, will be investigated. The gratings with the widest spacing will be located at the upper end of the experimental flume and those of the narrowest spacing at the lower end. The vertical depth of each individual vane is about 5 1/4 inches.

A number of 4-inch discharge-pipes, extending horizontally from the sides of the hopper, carry the effluent from the gratings. The discharge from the hoppers will be regulated by different sizes of orifices ranging from one to three inches in diameter. The rate of flow will be ascertained by noting the pressure-head on the orifice and applying the coefficient of discharge determined by calibrating the orifice for the particular condition. The several streams leading from the main structure are collected in two side channels at the sides of the grillage-foundation. These two streams join, discharging back into the River at a point about one-fourth mile below Rositas Dam. The discharge from the end of the main flume is first caught in a spill-box or outlet-structure, and then measured over a weir without end-contraction, the main stream then returning to the River.

These tests are now in progress, and it is still too early to predict the degree of success of either of these devices in capturing and retaining the fine sand and silt carried in the waters of Colorado River. Should either of these types of sand-traps prove efficient, the results of these studies may dictate the design of the desilting works for the All-American Canal to be built from the Colorado River to supply irrigation-water to the 600,000 acres of irrigated lands in the Imperial Valley of southern California.

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DISCUSSION OF "THE REMOVAL OF BED-LOAD FROM ARTIFICIAL CHANNELS" AND NOTES ON THE REMOVAL OF SUSPENDED LOAD, SILT, AND FINE SAND BY SPIRAL FLOW

F. W. Kerns and Warren Egbert

The writer of this paper is developing along three separate and distinct lines the solution of an age-old engineering problem in which little advancement has been made in modern times. The slow, cumbersome, and expensive process of the removal of solids from liquids by sedimentation, coagulation, and filtration is the only practical method heretofore available. The urgent need for some positive and economical method of desilting water is emphasized not only by conditions in rivers such as those of India and the United States, but also by the fact that 70 per cent of the municipal water-supply in the United States undergoes filtration, and practically all that is drawn from turbid rivers is subject to preliminary sedimentation at certain seasons if not throughout the year.

Without having seen them in operation, it is difficult to discuss intelligently desilting or desanding devices involving such radical departures from previous practice as those developed by R. L. Parshall; indulgence is therefore requested for a necessarily hesitant discussion.

The production of a true vortex in a horizontal pipe, with no actuating force other than that of the stream flowing across the pipe from which the downstream upper quarter has been removed is remarkable in itself. The wide range of angle allowable between the pipe and the axis of the stream is also something hardly to be anticipated. It seems reasonable to suppose that a flow rotating rapidly enough to produce a horizontal vortex would have a much greater scouring capacity, and would maintain solids in suspension much more readily than would a stream-line flow of equal linear velocity; but cobbles as large as golf balls kept in suspension, indicate an actuating force powerful enough to give unexpected results in the removal of a heavy bed-load. It would be interesting to know the percentage of the channel-flow necessary to carry off the solids in this particular device and whether it can be assumed that it removes the fine bed-load as readily as the coarse.

In the riffle-deflector trap, the cross-flow induced by the deflectors, carrying the sand with it, and the action of the sand in hugging the lower side of the vanes appear to be normal hydraulic actions; but this type of apparatus also develops an apparent paradox and actually moves the sand upstream when the deflectors are given the proper curvature and setting. The questions that naturally arise concerning this device are whether there is any tendency for the spaces between the vanes to become clogged with sand when the angle with the stream is abnormal and whether further tests will not be made with it at the Alamo River Laboratory.

Preliminary experiments only have been made with the grating type of trap, but from the studies of the action through a glass-sided flume, the downward action of the sand-grains at the downstream edges of the vanes, as well as the action of the potassium permanganate, indicate that this may prove the most successful device for the removal of bed-load. It appears particularly promising for the removal of the finer material. Of particular interest in this type would be whether the preliminary studies revealed any undulatory movement of the stream-lines as they passed alternately over the vanes and the spaces between them; and if so, whether there was any tendency for grains that had settled below the level of the tops of the vanes to be carried by such undulatory movement over the top of the next vane downstream. Of further interest would be whether a critical velocity was reached at which sufficient turbidity resulted to prevent normal settlement of the grains in the spaces between vanes.

The success of the horizontal vortex-tube in the removal of coarse material appears to be well established by past experiments; and if either it or the grating type of trap prove successful in removing a reasonable amount of the finer bed-loads, the engineering profession, as well as the immense areas having silt-problems, will be heavily indebted to Mr. Parshall for his versatile and pioneer work on a baffling engineering problem.

Notes on the removal of suspended load, silt, and fine sand by spiral flow

If water flows in an open curved channel, centrifugal action raises the outer surface above and depresses the inner surface below the normal level at the center. If the curved channel be closed, as in a covered flume of rectangular cross-section, the centrifugal effect manifests itself as additional pressure at the outside and reduced pressure at the inside of the flume. Each horizontal layer of water that is flowing fast enough to cause this centrifugal effect is of course flowing exactly fast enough to resist it. Both the bottom and top layers in a closed channel, however, are retarded by friction, and are therefore forced inward by the added head or pressure at the outside and the reduced head or pressure at the inside. As a consequence, there is a cross-flow imposed upon the longitudinal flow, the resultant of which has been aptly named "spiral flow."

The transverse components of this spiral flow form double closed circuits as in Figure 1, in a closed channel; the arrows indicate the direction of flow.

While making some experiments for the removal of sand from water centrifugally, the effect of spiral flow was observed. The water was stirred in a cylindrical vessel until it rotated quite rapidly, sand was then dropped into the water, and it was observed that the grains, while in suspension, moved away from the center due to centrifugal action, but that immediately upon striking the bottom of the vessel, they moved along the bottom toward the center more rapidly than they had moved outward while in suspension.

The sand invariably formed a cone on the bottom of the vessel at the center, the coarser grains segregating at the base of the cone and the finer grains climbing over

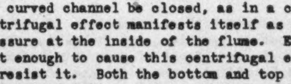

Fig. 1

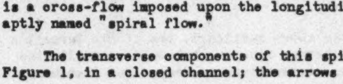

Fig. 3

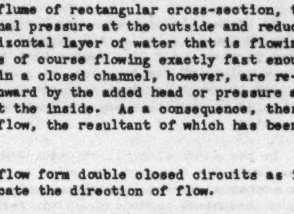

Fig. 2

the coarser. Upon reaching the apex of the cone at the center of rotation, the extremely fine grains "took off," spreading out due to centrifugal action as they ascended, until they formed an inverted cone in suspension, having much the same shape as the dust in a whirlwind.

A vertical section through the center of the cylindrical vessel appeared as in Figure 2, the arrows indicating the two complete circuits of spiral flow in a vertical section that is rotating at the same rate as the water.

After several years of intermittent experiment with centrifugal, centripetal, and combinations of the two actions, it became evident that centripetal or spiral-flow action was best suited for the removal of fine sand and silt from water, as it required no moving parts, no applied power, and no high rotational losses; in short, spiral-flow action offered a solution for the removal of fine sand and silt from a stream of water simply by the introduction of a curved channel into the stream.

The first experimental model was a channel 1 1/2 inches wide, 1/8 inch deep, and 8 1/2 inches outside diameter; the next channel was 3 by 3/16 inch and 14-inch outside diameter; the dimensions were then increased to what was considered the practical constructional limit of outside diameter, five feet, with a channel 1/2 by 12 inches. These models were all under glass so that the action could be readily observed and studied.

We are indebted to Fred C. Scobey of the United States Bureau of Agricultural Engineering, who first suggested that the action in these models might be due to spiral flow and called our attention to the experiments that had just been completed by D. A. Yarnell at the University of Iowa. Mr. Scobey also gave us the bibliography of spiral flow dating back to Sir James Thompson in 1876.

Mr. Yarnell's apparatus was a transparent conduit with cross-section 10 inches square, U-shaped in plan, the tangents being about 14 feet long and the radius of the curved portion about five feet. With this channel, and pieces of yarn attached to various points of its interior, he demonstrated beautifully the existence of spiral flow and the various closed circuits formed by the lateral components, but did not mention in his bulletin any application of spiral flow toward the removal of solids from water.

In the model with 5-foot outside diameter above mentioned, one of Mr. Yarnell's experiments was repeated, in order to learn whether his results could be duplicated with a channel a little wider and only about one-twentieth as deep. The upstream ends of two black threads about six inches long were attached to the top and bottom of the closed channel, and a red thread at mid-depth to a fine needle, the three points of attachment being in the same vertical line. When the flow was admitted, the three threads extended down stream in straight lines, the upper black thread being directly above the lower black one for its entire length, both making an inward angle from the tangent to the curve at the point of attachment of about 15°; the red thread made an angle outward from the tangent of about 15°.

Mr. Yarnell's deductions as to an inward spiral flow across the top and bottom of a curved closed channel and a return outward spiral flow at mid-depth were further verified by introducing larger and larger grains into the channel. As the size of grains increased, their movement toward the center became more sluggish, and upon introducing a bead with diameter slightly less than the channel depth, it moved outward. The single inward flow across the bottom, striking the bead approximately only at its point of tangency with the bottom, proved less effective than the double outward flow at mid-depth, striking approximately at the bead's greatest diameter.

As the spiral flow does not extend into the corners of a rectangular channel but curves as shown in Figure 2 of Mr. Yarnell's diagrams, there is a slight tendency for small bars to form on a horizontal bottom at the inner edge if the velocity is too low. Saltation always occurs at these bars, the sand-grains climbing up the flat outer slope and tumbling down the steeper inner slope to enter the silt-wells. If the bars become of any appreciable size, the reduction formed in the channel cross-section automatically results in an increased velocity which either carries the bars into the wells or forms a stable channel with continuous saltation. The barring was completely eliminated by bending the inner edge of the channel down at an angle of 30° from the horizontal, Figure 4, the gravitational effect on the slope acting in conjunction with the spiral flow to move all of the sand into the wells.

The fourteen-inch outside diameter model was small enough to tip at any angle from the horizontal; at an angle of 30° the sand still climbed the slope almost as readily as when in a horizontal position, and it was necessary to tip it up to about 45° from the horizontal before the effect of the spiral flow was completely neutralized.

In this apparatus, the sand crossed the 3-inch channel from outside to inside in about 120° of curvature, a lateral movement of about one inch per 3.8 inches of mean circumference. In the apparatus with 5-foot outside diameter, the lateral movement was about one inch per 5.8 inches of mean circumference.

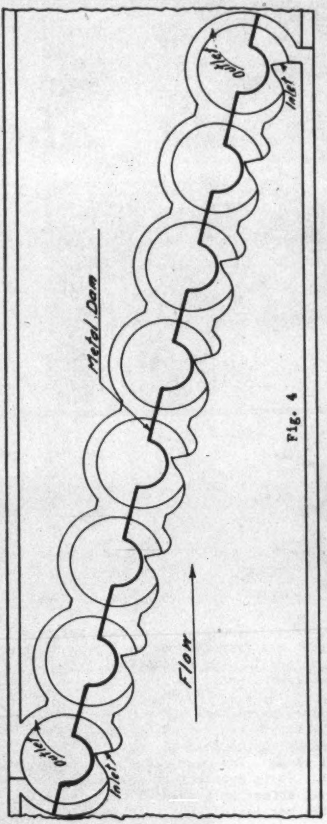

Fig. 4

The best average velocity for fine sand in either apparatus was about 1.25 feet per second, being somewhat higher for a large percentage of coarse sand, and smaller for a small percentage of finer material. The extreme velocities ranged from about 0.50 to 1.50 feet per second, the lower velocity being capable of moving only clay or solids having a specific gravity considerably less than that of sand, while the upper velocity tended to keep fine sand in suspension.

Roughness of the channel-bottom had little apparent effect on the inward movement of the solids; they climbed over a blistered or scaled surface as readily as they climbed over sand-bars.

The 5-foot outside diameter model removed 90 per cent of Sacramento River sand and silt, 96 per cent of which passed a No. 100 sieve, 42 per cent passed a No. 200, and 12 per cent passed a No. 270.

For a definite size of sand-grains and a fixed depth of channel, a constant time-interval must be allowed for the grains to settle as there is no lateral inward movement due to spiral flow until they are on or very near the bottom. In fact, there is a slight outward movement while the grains are in suspension and settling through the double outward spiral flow at mid-depth. By reducing the channel-depth, the time allowed for settlement is shortened while the time required for lateral movement is correspondingly increased, resulting in a larger percentage of removal.

In a multiple-channel apparatus the load of solids on a plate is reduced as the channel-depth is decreased. Multiple channels are of course necessary to obtain capacity, the practical height of a nest of plates being about 15 feet, which gives a capacity of about 17 second-feet per unit or nest. The installation of multiple units, as shown in Figure 4, gives capacity sufficient to handle any desired flow.

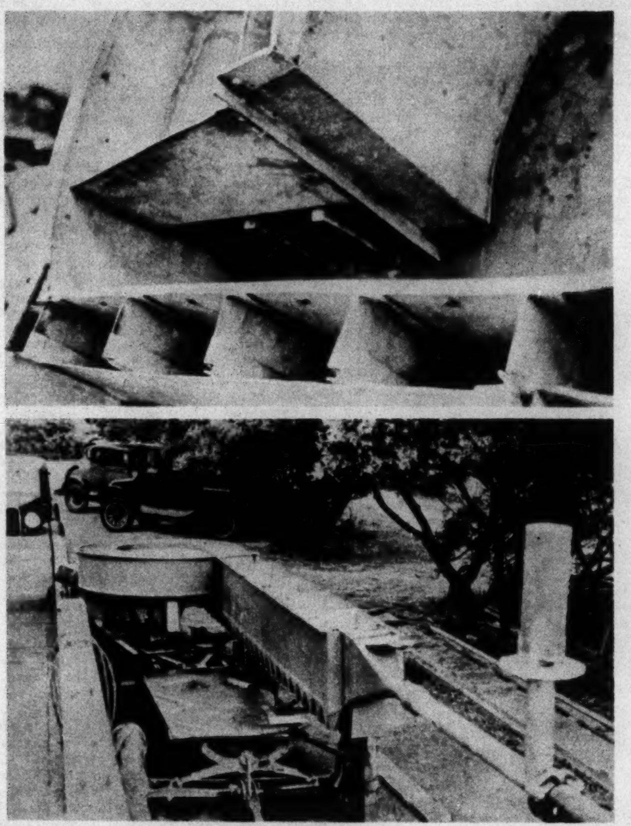

Fig. 5--Sand-feed in foreground of lower view at right; upper view into silt-wells

The fact that a considerable portion of a curved channel is used only for sedimentation, particularly where the removal of extremely fine sand or silt is involved, led to further investigation for a simple form of preliminary sedimentation-channel that might be constructed in combination with a circular portion.

Experiments were therefore made with a tangential channel under glass. As it was considered desirable, in a circular commercial unit, to add a gravitational effect to that of spiral flow, particular attention was given to the possible removal of large grains in a tangential channel having a lateral slope. The best slope was determined empirically to be about 25° from the horizontal. It is apparent of course that there is an optimum slope, as there is no gravitational effect in a channel that is horizontal transversely, while if turned 90° from the horizontal, the settlement-depth is increased to the full width of the channel.

The experimental tangential channel, three-eighths inch deep, nine inches wide, and eight feet long, removed 90 per cent of Colorado Desert sand ranging in size from No. 16 sieve to passing No. 300, and 97 per cent of this sand retained on No. 200 sieve was removed. Little was expected of this channel in the removal of extreme fines, but a test made with suspended material that had been carried some 70 miles in the ditches of the Imperial Valley and deposited in rice-fields near El Centro, gave a removal of 18 per cent; 99.7 per cent of this material passed a No. 100 sieve, 93.8 per cent passed No. 200, and 60.1 per cent passed No. 300. Incidentally an analysis of milled ore caught in the wells of this tangential channel showed it to be an excellent classifier.

In the design of commercial units composed entirely of tangential channels for the removal of sand ranging down to about No. 200 sieve, the capacity of a unit may be increased to about 42 second-feet by using plates 30 inches wide shaped to the form of a gable roof so that the solids slide down the two lateral slopes in opposite directions.

A combination of tangential and circular multichannel experimental apparatus is shown in Figure 5. It has 13 channels, three-eighths inch deep and 12 inches wide; the tangential portion is 12 feet long, the circular portion has an average length of 10 feet, the lateral slope of the plates is 25°, and the capacity at the average velocity of 1.25 feet per second is a little over one-half second-foot. This apparatus was designed to remove approximately all material down to 0.033-millimeter diameter, corresponding to a No. 450-sieve size.

Tests at the Berkeley Airport and at the California Institute of Technology at Pasadena showed an average removal of about 65 per cent of the above-mentioned material taken from the rice-fields near El Centro. A microscopical examination of these grains showed that approximately 50 per cent of the total area of those examined was composed of grains less than 0.033 millimeter, so that the apparatus was apparently effecting a removal a little better than that for which it was designed.

The friction-head loss in this apparatus, as determined with an engineer's level, was almost exactly one-hundredth of a foot per foot of length, at the normal velocity of a little less than 1.25 feet per second.

Tests of removal of sand from the silt-wells indicate that, under a head as low as two feet, approximately four-tenths of a cubic foot of wet sand per minute can be withdrawn through a circular opening seven-eighths inch in diameter. The material so withdrawn consisted of two parts of sand to one part of water by weight.

Where diversion of sand- and silt-laden water is made from a stream, the silt-wells may all be connected to a common pipe and the solids returned to the stream with dredging pumps, if the water-supply be plentiful.

In general, all methods for the removal of solids from liquids are based on sedimentation; the time necessary for sedimentation is directly proportional to the settlement-depth, so that if the depth can be reduced from feet to fractions of an inch by multiple-channels, and the solids automatically removed in a high state of concentration into wells from which final disposition may economically be made, the efficiency of the process is definitely improved.

Berkeley, California

VARIED FLOW IN OPEN CHANNELS WITH ADVERSE SLOPE

Arthur Matzke

This paper, to be published elsewhere, was presented in preliminary form for the author by Dr. B. A. Bakhmeteff.

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TEMPERATURE-DIVERGENCES BETWEEN VALLEY- AND MOUNTAIN-STATIONS

George V. Sager

The title of this paper is perhaps a little misleading. It is not a study of temperature-divergences in general but of one specific problem in one locality. The specific proposition to be discussed is: What relation do the temperature-departures from normal at the mountain-stations, Tahoe and Summit, California, and Marlette Lake, Nevada, for any month bear to the departure from normal at Reno for the same month?

The study was made to ascertain to what extent the temperature-departure at Reno, always immediately available, could be taken as indicative of the departure at the nearby mountain-stations, thus giving a clue to the probable melting of snow in the mountains, runoff, and snow-wastage by evaporation.

Reno is located in Truckee Valley, a few miles east of the foot-hills of the Sierra Nevada, at an elevation of 4527 feet. Tahoe is on the westerly side of Lake Tahoe at its outlet, at an elevation of 6230 feet. Summit is very close to the summit of the Southern Pacific Route over the Sierra Nevada--hence the name--at an elevation of 7017 feet. Beginning with January 1927, the station was moved to Norden--a little farther west--at an elevation of 6871 feet, and in January 1931 it was again moved two or three miles westward to Soda Springs at an elevation of 6752 feet. Marlette Lake is on the westerly side of the artificial lake of that name, the reservoir from which water is drawn to supply Virginia City, at an elevation of 8000 feet.

The immediate surroundings of Tahoe are level. Summit is in an irregular canyon sloping to the southwest. Marlette Lake Station is not far from the level of the Lake.

Records of temperature for the 24 years from 1910 to 1933 are available for Tahoe. This period was therefore chosen as the unit for study. Monthly temperatures for these 24 years were tabulated for Reno, Summit, and Tahoe,and monthly means were computed. These means were used as normals for the stations for the purposes of this study. Records for only eight to nine years are available for Marlette Lake. The monthly averages for this period were taken for all the stations, and, by comparison with the 24-year records, the probable means at Marlette Lake for the 24-year period were computed and used as normals for that Station.

These normals were tabulated, and the departures of those of the mountain-stations from that of Reno were taken individually and the average of these departures was then computed as given in Table 1.

Monthly departures from normal were then computed for each of the stations and the means of the departures for the three mountain-stations were taken month by month to represent the average departure for the mountain-area.

The departures at Reno were then divided into three groups: (1) Those for months with a departure from the normal of plus or minus 2° or less, or the "near-normal" group; (2) those for warm months--months with plus departures of more than 2°; (3) those for cold months--months with minus departures of more than 2°. The corresponding departures at each of the mountain-stations were tabulated opposite those for Reno, as was also the departure of the average of the three mountain-stations. Group-means and the divergences of the group-means of the mountain-stations and of those for the entire period from those at Reno were then computed and tabulated as in Table 2.

From the table of temperature-departures at Reno and the mountain-stations the greatest plus divergences and the greatest minus divergences of the mean departures of the mountain-stations from the departures at Reno were taken by months and tabulated as in Table 3.

Table 1--Normal temperatures 24-year period, 1910-1933

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
Reno	31.8	36.3	43.1	48.0	55.7	63.8	71.8	69.8	61.2	51.8	42.1	33.6
Tahoe	26.4	28.5	32.9	37.6	45.3	53.1	60.7	59.9	53.0	44.4	35.8	28.8
Summit*	26.8	28.1	31.2	35.3	43.5	52.0	58.8	57.7	52.2	45.0	35.8	28.3
Marlette Lake	23.8	25.7	28.9	33.6	41.8	51.2	60.4	58.4	50.1	41.2	34.0	26.0
Departures from Reno normal												
Tahoe	-5.4	- 7.8	-10.2	-10.4	-10.4	-10.7	-11.1	- 9.9	- 8.2	- 7.4	-6.3	-4.8
Summit*	-5.0	- 8.2	-11.9	-12.7	-12.2	-11.8	-13.0	-12.1	- 9.0	- 6.8	-6.3	-5.3
Marlette Lake	-8.0	-10.6	-14.2	-14.4	-13.9	-12.6	-11.4	-11.4	-11.1	-10.6	-8.1	-7.6
Average departures 3 Mt.-stations	-6.1	-8.9	-12.1	-12.5	-12.2	-11.7	-11.8	-11.1	-9.4	-8.3	-6.9	-5.9

*From the three stations Summit, Norden, and Soda Springs.

Table 2--Average monthly temperature-departures (either plus or minus) from normal at Reno and mean average temperature-departures at the three mountain-stations

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
24-year period 1910-1933												
Reno	+3.6	+3.7	+2.6	+2.3	+3.2	+2.1	+1.8	+1.7	+1.8	+2.5	+2.3	+2.9
3 Mt.-stations	+2.4	+2.6	+2.5	+2.6	+3.6	+2.3	+1.9	+2.0	+2.1	+2.6	+2.6	+2.7
Mt.-sta.>Reno	...	...	...	0.3	0.4	0.2	0.1	0.3	0.3	0.1	0.3	...
Mt.-sta.<Reno	1.2	1.1	0.1	...	...	...	...	...	...	...	...	0.2
"Near-normal" months, between +2°.0 and -2°.0, inclusive												
Number years	9	8	10	12	7	15	16	13	14	13	11	10
Reno	-0.1	-0.1	+0.2	-0.2	+0.5	+0.1	+0.2	-0.1	0.0	0.0	+0.1	-0.2
3 Mt.-stations	-0.7	-0.2	+0.8	-0.4	+0.2	+0.1	+0.3	+0.4	+0.2	-0.1	+0.4	-0.2
Mt.-sta.>Reno	0.6	0.1	0.6	0.2	...	0.0	0.1	0.5	0.2	0.1	0.3	0.0
Mt.-sta.<Reno	...	...	...	...	0.3	0.0	...	...	...	...	...	0.0
Warm months, +2°.1 or more												
Number years	10	9	6	6	7	4	3	5	5	6	6	6
Reno	+3.7	+4.4	+3.8	+3.7	+4.8	+4.7	+3.9	+3.1	+3.5	+3.8	+3.7	+5.2
3 Mt.-stations	+2.2	+3.0	+3.8	+4.2	+5.3	+4.2	+3.4	+2.3	+3.4	+3.5	+2.6	+4.5
Mt.-sta.>Reno	...	...	0.0	0.5	0.5	...	...	...	...	...	...	...
Mt.-sta.<Reno	1.5	1.4	0.0	...	...	0.5	0.5	0.8	0.1	0.3	1.1	0.7
Cold months, -2°.1 or more												
Number years	5	7	8	6	10	5	5	6	5	5	7	8
Reno	-7.3	-5.4	-4.1	-3.4	-3.8	-3.3	-3.2	-2.6	-3.4	-4.8	-3.4	-3.6
3 Mt.-stations	-3.2	-3.5	-3.4	-3.5	-3.9	-3.1	-3.1	-3.1	-3.8	-4.0	-3.3	-2.9
Mt.-sta.>Reno	...	...	...	0.1	0.1	...	...	0.5	0.4	...	...	...
Mt.-sta.<Reno	4.1	1.9	0.7	...	...	0.2	0.1	...	...	0.8	0.1	0.7

For slightly less than two-thirds of this period the means of Tahoe and Summit, only, were available to represent the mountain-area, in computation of the divergences.

As would be anticipated from ordinary observation and experience, the 24-year means at the mountain-stations are consistently lower than those at Reno. There are, however, some interesting variations in the degree of departure at the various stations

Table 3--Greatest divergences of temperature-departures for Reno and for three mountain-stations

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
Reno departure minus and average departure for mountain-station greater												
Reno	-2.0	-1.5	-2.1	-1.0	-5.6	-2.0	-4.0	-2.2	-2.8	-1.2	-3.5	-4.6
3 Mt.-stations	-5.2	-3.0	-3.2	-2.8	-7.9	-5.9	-6.3	-4.4	-5.0	-2.4	-5.9	-6.8
Divergence	3.2	1.5	1.1	1.8	2.3	3.9	2.3	2.2	2.2	1.2	2.4	2.2
Reno departure minus and average departure for mountain-stations smaller												
Reno	-9.0	-2.7	-4.8	-1.4	-5.7	-1.0	-2.8	-2.7	-3.0	-6.8	-0.3	-3.2
3 Mt.-stations	-3.2	+1.7	-2.2	-0.6	-4.2	+1.1	-0.8	-1.6	-1.1	-4.2	+4.2	-0.6
Divergence	5.8	4.4	2.6	0.8	1.5	2.1	2.0	1.1	1.9	2.6	4.5	2.6
Reno departure plus and average departure for mountain-stations greater												
Reno	+3.4	+3.1	+3.7	+3.0	+4.0	0.0	+1.0	0.0	+0.3	+1.4	+1.3	+1.9
3 Mt.-stations	+4.6	+4.0	+5.7	+4.8	+6.0	+1.2	+2.6	+2.8	+0.7	+4.8	+4.4	+5.0
Divergence	1.2	0.9	2.0	1.8	2.0	1.2	1.6	2.8	0.4	3.4	3.1	3.1
Reno departure plus and average departure for mountain-stations smaller												
Reno	+5.0	+2.5	+3.8	+1.0	+0.8	+1.4	+0.4	+4.4	+1.5	+3.0	+3.5	+6.0
3 Mt.-stations	+2.0	-0.6	+1.6	-0.2	0.0	-0.4	-1.4	+2.5	-0.6	+0.2	-0.2	+1.8
Divergence	3.0	3.1	2.2	1.2	0.8	1.8	1.8	1.9	2.1	2.8	3.7	4.2

during different months. Tahoe averages about 5° colder than Reno during December and January. Summit, 800 feet higher, averages practically the same as Tahoe. In February the average is 8° colder than Reno for both stations. During March, April and May, Tahoe is about 10° colder than Reno, while the departure at Summit has increased to 12°. During the summer months the differences are 11° for Tahoe and 12° for Summit. During November they are exactly alike at 6°.3 lower than Reno. At Marlette Lake the departures below the averages at Reno are 2° to 3° greater than at Tahoe, except in July, when both are 11° lower than at Reno. The discrepancies between Summit and the other two stations in winter are probably due to more active air-drainage at Summit neutralizing, to some extent, the local effects of radiation while in summer this effect is not so much in evidence.

When the departures from the normals are scanned, wide variations are found in individual months at the various stations. As a rule, the departures are consistent with each other, that is, all minus or plus departures for the same month, though verying in degree. Most of the reversals of sign occur with small departures at Reno, when a small discrepancy may change the sign of the departure, but there are occasional discrepancies hard to explain. Moreover, the departures at Summit, either plus or minus, are often so much greater than at either Tahoe or Marlette Lake as to lead one to suspect imperfect exposure. This was the case, as the instrument-shelter, while the station was at Summit, was situated inside the car-sheds, which would doubtless considerably modify the readings. In its later location at Norden the exposure was much better, while at Soda Springs it has been excellent. In one particular instance in February 1917, the departures at the other mountain-stations were 1° to 3° less than at Reno, while Summit recorded 8° greater than Reno. It would seem that during this particular month there must have been some additional source of error in the readings. But the net result of these discrepancies is small, so all records have been used and given equal weight in the study.

When the magnitudes of the average departures are taken we find them greatest in winter and least in summer. During the months December to March the average departure from normal at the mountain-stations is less than at Reno, while during the remaining eight months of the year it is greater. The greatest difference is in January when the average departure from normal is 3°.6 while at the mountain-stations it is 2°.4, or 1°.2 less. In February the difference is 1°.1, in March it is only 0°.1, in December 0°.2. The differences, April to November, when the departures from normal at the mountain-stations average greater than at Reno, are uniformly small, ranging from 0°.1 in July and October to 0°.4 in May. In other words, the average departures from normal during ten months of the year are the same at Reno and at the mountain-stations, taken as a group, to within 0°.4, and in January and February they average slightly more than 1° smaller at the mountain-stations than at Reno.

When the means of the "near-normal" group--which includes all months in each of the years studied in which the departures at Reno ranged from 2° below normal to 2° above normal--are considered, we find that in June, during 15 years when the departure at Reno was within these limits, the average departure at the mountain-stations and at Reno was identical, namely, 0°.1 above normal. The average at Reno and in the mountains was the same for ten such Decembers, namely, 0°.2 below normal. Those for three other months, February during eight years, July during 16, and October during 13 years, differed by only 0°.1. The average in August during 13 years was -0°.1 at Reno and +0.4 at the mountain-stations, a difference of 0°.5. In March, for ten years, the average departure at Reno was +0°.2, at the mountain-stations +0°.8; in January, for nine years, the average departure at Reno was -0°.1, at the mountain-stations -0°.7; thus in each of these two months the departure at the mountain-stations was 0°.6 greater than at Reno. In May, the average departure at Reno was +0°.5, and the average at the mountain-stations was +0°.2. This is the only instance in the averages of the "near-normal" group in which the departures at the mountain-stations average less than those at Reno. Summing up for this group, the departures at the mountain-stations in May average 0°.3 less than at Reno; during the remaining 11 months they average from 0°.0 to 0°.6 greater than at Reno.

Let us next consider the "warm" group which includes all of those individual months in which the temperature-departure from normal at Reno was greater than 2°. The number of such months during the 24-year period ranges from three in July to ten in January. The average departure at Reno ranges from 3°.1 in August to 4°.8 in May. In March the average departure from normal was the same in the mountains as at Reno, 3°.8. In April and May it was 0°.5 greater in the mountains than at Reno for the average of six years in April and seven years in May. For the nine months June to February, the departures from normal were smaller in the mountains than at Reno. The greatest divergences during these months were 1°.1 in November, 1°.4 in February, and 1°.5 in January. So for this "warm" group of departures we find that for nine months of the year, when Reno had a monthly temperature-departure above normal greater than 2°, the mean departure from normal at the mountain-stations varied less than 1° from that at Reno, while for November, January, and February it was a little more than 1° smaller than at Reno.

Let us now consider the third group, which includes those months in which the temperature-departure from normal at Reno was negative and greater numerically than 2°. The number of times during 24 years when this occurred ranges from five times each in January, June, July, September, and October to ten in May. For the months April, May, August, and September, the average departure at the mountain-stations was from 0°.1 to 0°.5 greater; for the remaining eight months it was less at the mountain-stations than at Reno. For the months March, June, July, October, November, and December, the average departures in the mountains were 0°.1 to 0°.8 smaller than at Reno; for February, the average departure, covering seven years, was 5°.4 below normal at Reno and 3°.5 below normal at the mountain-stations, the departures in the mountains thus averaging 1°.9 smaller than those at Reno. For January there are five years in this group with an average of 7°.3 below normal at Reno. At the mountain-stations the average for these five years was 3°.2 below normal, 4°.1 less than at Reno. The divergences are thus greater in January than in any other month and greatest for this month when the temperature at Reno averages considerably below normal.

Glancing for a moment at the divergences in individual months, we find that in November 1929 the average at Reno was -0°.3 while the average at the mountain-stations was +4°.2, a divergence of 4°.5. This is the greatest plus divergence of the temperatures of the mountain-stations. In January 1917 the temperature-departure at Reno was -9°.0; that of the mountain-stations was -3°.2, a divergence of 5°.8. This is the greatest divergence when the temperature in the mountains averaged nearer to normal than did that at Reno. In January 1916, however, when the departure at Reno was likewise -9°.0, the divergence was 4°.1, or 1°.9 less than in the succeeding January.

Out of the 288 months of the 24-year period studied, 246 had divergences of 2° or less and 42 had divergences of more than 2°. Thirty-two of these latter occurred

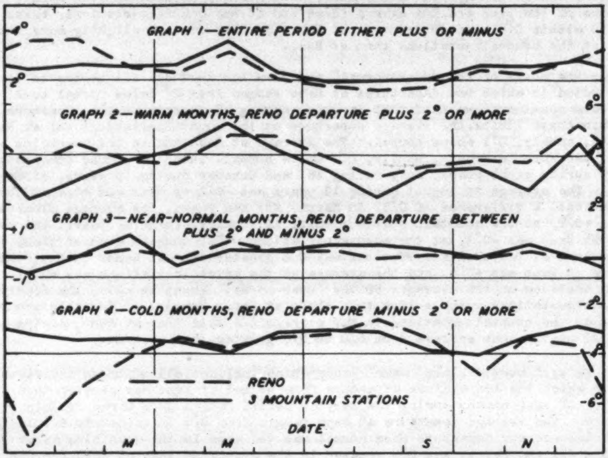

FIG. 1—TEMPERATURE-DEPARTURES, 1910-1923

in the four months, November to February, and only ten during the remaining eight months. For the 107 months of the period when the records of Marlette Lake were available, the number of times with departures of 2° or less was 90; the number of departures of more than 2° was 17. For the 181 months when the mountains were represented by two stations only, Tahoe and Summit, the number of months with departures of 2° or less was 156; with more than 2°, 25. The proportions are 6.2 to 1 when two mountain-stations are available, 5.3 to 1 when three are available. These proportions apparently indicate that the inclusion of Marlette Lake slightly increases the average departure of the mountain-stations, but the results are not sufficiently different to be conclusive.

The results of this investigation are graphically shown in Figure 1. Graph 1 on this Figure shows the average departures from normal at Reno and the mean of the average departures at the three mountain-stations. It will be seen at a glance that January and February are the only months in which there is any appreciable divergence. Graph 2 shows the average departures when the departure at Reno is plus and greater than 2°; Graph 3 shows the average departure when that at Reno is 2° or less, either plus or minus; Graph 4 shows the average departures when that at Reno is minus and numerically greater than 2°.

Here we see at a glance that the divergences, either plus or minus, during the spring, summer, and fall months, are, on the average, negligible. During the winter months it is seen that the average divergence is small when the temperature at Reno averages near to normal; that it is larger when the temperature at Reno averages more than 2° above normal, the divergence being caused by the departures being smaller at the mountain-stations; and that it is largest of all when the minus departures at Reno average large, the temperatures at the mountain-stations departing much less from normal than those at Reno.

Summary--(1) The trend of the temperature-departures at the mountain-stations is shown to be usually the same as that at Reno with the departures from normal, on the average, slightly larger in the mountains during the warm months than at Reno and considerably smaller in the mountains than at Reno during the cold months. The divergences are shown to be usually greatest when the temperature at Reno departs farthest from the normal and are especially large with large negative departures at Reno during the winter months.

I shall not go far in attempting to account for these divergences, but shall content myself with suggesting the two most probable reasons for most of them. First, cold periods in winter in this region are caused by a flow of air from the polar regions southward. When this moving mass of cold air is deep enough to extend upward well above the mountain-stations, all stations in the area will have subnormal temperatures and the divergences will be small. When the mass of cold air is shallow, the cold air will engulf only the stations at lower elevations, or, if deep enough to just cover the high stations, will quickly drain away from them and the temperature-departures below normal at Reno will be much greater than at the mountain-stations. An occasional cold period of this type in any month could readily account for the negative departures in the mountains for that month averaging smaller than at Reno. Tahoe and Marlette Lake, being in partially enclosed valleys from which air-drainage is slow while Summit is on a slope with rapid drainage, may largely supply the reason for many of the apparent discrepancies noted between their respective temperature-departures.

(2) It is a well-known fact that radiation from a snow-surface is greater than from a land-surface. Reno is seldom snow-covered. The snow-cover in the mountains varies much at times at the different stations. In fall and spring especially, owing to drifting and melting, there may be wide variations in the amount of land- and snow-surfaces at the various stations. Under such conditions when air-movement is slow and radiation favored, considerable variations in temperature may result. These two considerations seem ample to me to account for most of the larger divergences. The smaller ones can well be considered a normal condition as no two stations ever follow exactly the same regime of temperature.

U. S. Weather Bureau,
Reno, Nevada

EVAPORATION AT HIGH ALTITUDES

J. E. Church

(Abstract)

This is a popular presentation of the formal paper on "Evaporation at high altitudes and high latitudes" presented for the writer at the meeting of the Section of Hydrology at Washington, D. C. That paper appears in full in these Transactions.

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FLOW-CHARACTERISTICS OF GLACIER-FED AND SNOW-FED STREAMS

Richard G. Tyler

Those who have made studies of the flow-conditions of streams rising in the higher altitudes and fed in part from snows and glaciers are quite familiar with the fact that these streams differ in certain very definite respects from those not thus favored. These differences include: (1) A more uniform flow throughout the year and a smaller coefficient of variation, as computed by Hazen's method; (2) higher annual runoff per square mile resulting from the greater precipitation at the higher altitudes; (3) excessive flood-flows arising from a combination of rainfall and melting snow; and (4) diurnal flow-variations produced by temperature-fluctuations at the higher altitudes.

While the above characteristics are generally recognized, quantitative data as to their magnitude and effect are not numerous. The purpose of this paper is to add some material to that which is being rapidly accumulated by organizations such as the

Table 1--Runoff data for Washington streams

No.	River	Location	Coefficient of variation	Mean annual flow	Drainage area	Mean		Maximum	Years record
				c.f.s.	sq.mi.	inch/yr.	c.f.s./sq.mi.		
1	Baker	Near Concrete	0.139	1990	184	146.5	10.80	200	18
2	Cowlitz	Mossy Rock	0.230	5270	1170	61.0	4.5	...	7
3	Hoh	Near Spruce	0.161	1890	193	132.6	9.8	118	6
4	Kalama	Kalama	0.220	1100	184	80.8	5.9	14.2	11
5	Lewis	Near Amboy	0.184	4110	665	83.5	6.2	25.0	18
6	Nisqually	Near LaGrande	0.218	1230	287	58.0	4.3	68.0	12
7	Puyallup	Puyallup	0.200	3150	914	46.6	3.4	62.4	18
8	Sauk	5 mi. above mouth	0.185	4220	714	79.8	5.9	96.0	17
9	Toutle	Below Forks	0.276	1970	472	56.4	4.2	....	7 [a]
10	White	Buckley	0.191	1470	424	46.9	3.5	40.1	14 [b]
11	Bumping	Near Nile	0.268	285	68	56.7	4.2	76.3	23 [c]
12	Chelan	Chelan	0.212	2030	950	28.9	2.1	12.2	29 [c]
13	Cedar	Landsberg	0.205	719	135	72.0	5.3	58.2	30 [c]
14	Clark Fork	Priest Rapids	0.234	26300	24200	14.7	1.1	9.0	24 [c]
15	Cle Elum	Near Roslyn	0.215	890	202	59.6	4.4	92.5	29 [c]
16	Chiwawa	Near Leavenworth	0.257	521	181	39.0	2.9	13.3	18
17	Columbia	Trail	0.135	72000	34000	28.7	2.1	9.1	19
		Kettle Falls	0.177	98900	64500	20.7	1.5	7.3	19
		Grand Coulee	0.182	107200	74100	19.5	1.4	6.6	19
		Wenatchee	0.189	119000	95500	17.0	1.3	7.7	17
		The Dalles	0.177	206000	237000	11.8	0.9	4.9	50
18	Entiat	Entiat	0.237	525	419	17.0	1.3	...	9
19	Elwha	Near Port Angeles	0.231	1400	262	72.2	5.3	91.0	14 [c]
20	Kochess	Near Easton	0.211	280	63	60.1	4.4	....	29 [c]
21	Okanogan	Okanogan	0.173	2900	7740	5.1	0.4	....	14
22	Quinault	Quinault Lake	0.185	2660	264	136.3	10.1	140.0	18
23	Sauk	Darrington	0.198	1990	293	91.8	6.8	123.0	16 [d]
24	Skagit	Below Ruby Creek	0.199	3230	978	44.7	3.3	46.7	22
		Newhalem	0.195	4330	1160	50.5	3.7	51.7	24 [e]
		Sedro Woolley	0.150	16200	2970	73.7	5.4	....	16
25	Skokomish, North Fork	Near Hoodsport	0.246	720	92	106.0	7.8	96.0	19 [c]
26	Skykomish, South Fork	Near Index	0.187	2310	355	87.9	6.5	161.0	21
27	Snoqualmie, North Fork	Near North Bend	0.161	680	105	87.5	6.5	106.0	22 [f]
	Middle Fork	Near North Bend	0.172	1180	173	92.0	6.8	106.0	22 [f]
	South Fork	Near North Bend	0.205	520	84	83.7	6.2	....	22
28	Spokane	Post Falls, Idaho	0.345	6060	3880	21.2	1.6	10.5	20 [g]
		Spokane	0.284	6900	4350	21.5	1.6	11.3	41
		Below Little Falls	0.317	7550	6380	16.0	1.2	6.5	20
29	Tieton	Hdwks Tieton Canal at Naches	0.225	540	240	30.4	2.2	25.6	22 [c]
30	Wenatchee	Leavenworth	0.190	2220	591	50.8	3.8	....	18
		Cashmere	0.206	3450	1200	38.9	2.9	....	13 [h]
31	Yakima	Near Martin	0.194	320	55	78.7	5.8	134.0	28 [c]
		Cle Elum	0.238	1920	500	51.9	3.8	51.2	26 [c]
		Yakima	0.206	4930	3650	18.8	1.4	14.9	23

[a] Record not continuous. [b] Includes amounts diverted into Lake Tapps. [c] Corrected for storage. [d] 1927-28 missing. [e] 1914-20 by comparison with Reflector Bar. [f] 1927-29 missing. [g] Includes flow in Spokane Valley Farms Company's canal. [h] Includes flow in Wenatchee Valley canal.

Western Interstate Snow-Survey Conference that may be useful in determining the capacity or usefulness of the streams.

In a recent paper (J. Amer. W. W. Assoc., v. 25, p. 94, 1933) I discussed some of the peculiar characteristics of the streams of the Pacific Northwest under the title "Storage requirements for northwestern streams." At that time I computed the coefficient of variation as recommended by Hazen (Civil Engineers Handbook, 6th Ed., pp.

1446-1452) for a number of rivers in Washington and Oregon and commented on the smaller storage-capacity that was required for a given demand than was necessary with streams in other sections of the country. Fred F. Henshaw has made a valuable contribution to the study of the flow-variations of such streams in his paper "Notes on variations of runoff on the Pacific Slope" (Trans. Amer. Geophys. Union, Fourteenth Annual Meeting, pp. 431-435, 1933). My former figures have been brought up to date and considerably expanded in Table 1.

As the late Allen Hazen has stated, the two most important factors in the study of flow-conditions of a given stream are its mean annual flow and its coefficient of variation which measures the amount by which the flow year by year varies from this mean. The coefficient of variation c v is defined by the formula

$$c\ v = \sqrt{\Sigma v^2/(n - 1)}$$

where v = percentage variation of each year's flow from the mean annual flow, M.A.F., and n = the number of years for which a record is available.

This coefficient is the best single term for giving an idea of the variability or the dependability of a given stream. The smaller the coefficient of variation the less do the annual flows vary from the mean. Referring to Table 1, the first ten streams are fed by glaciers in addition to the snow accumulating in the higher altitudes. Many of the other streams are largely influenced by snowfall, while some of them have particularly satisfactory conditions for ground-storage which aid materially in increasing minimum flows. It will be noted that the coefficients of all such streams are low as compared with those of other streams in the Table. A stream with a coefficient of variation of 0.20, for example, has an unusually steady flow from year to year, requiring a minimum of storage to supply a given demand.

The coefficient of variation of a stream usually increases toward its mouth, though the reverse may be sometimes encountered. The Columbia River, for example, illustrates the type with an increasing coefficient of variation. This condition arises largely because in its lower reaches its tributaries have higher coefficients of variation, thus increasing the fluctuations in flow in the main stream. The Skagit River, on the other hand, has a decreased coefficient of variation below its tributary, the Baker River, because of the very low coefficient of variation of the latter. There is no very definite relationship between coefficient of variation and area but this coefficient is a function of the amount and regularity of the precipitation, and of the ground- and snow-storage in the drainage-area. There is no apparent distinction between the coefficients of variation of streams fed by glaciers and snow and those fed primarily by rainfall where there is a similar total precipitation. Henshaw calls attention in the article above mentioned to the larger number of streams with a low coefficient of variation for Alaska than for Hazen's data on streams in the eastern United States. The State of Washington has some streams of both varieties. Figure 1 reproduces the Henshaw and Hazen curves mentioned, superimposed on the writer's data for British Columbia and Washington. There seems to be a dearth of streams between these two groups or with a coefficient of variation of 0.15 to 0.17. This Figure emphasizes the tendency of precipitation- and flow-conditions to produce streams with coefficients of about 0.125 and 0.190, respectively.

With respect to the higher annual runoff per square mile that prevails for snow-fed streams, this also is a function of total annual precipitation rather than the proportion of snowfall on the drainage-area. The principal advantage of snow in a watershed is, of course, that it distributes the runoff so that it is proportionately greater during the summer months than where the precipitation is in the form of rain. In the writer's paper already referred to, this snow-storage on the Cedar River watershed produced its peak-discharge some four or five months later than the peak-precipitation, making April to June the period of high runoff. (This is shown in Fig. 5 reproduced herewith.) It is interesting to compare the Baker and Quinault rivers to show that there is little difference in total annual runoff between streams with and without significant snow-storage. The former, fed by snows and glaciers, has an average runoff of 146.5 inches depth per year, or 10.8 c.f.s. per square mile for a drainage-area of 184 square miles. The precipitation in this drainage-area may be approximated by the figure for Baker Lake of 133.39 inches per year, including 104.0 inches snowfall, and Mt. Baker Lodge with 96.85 inches total precipitation, including

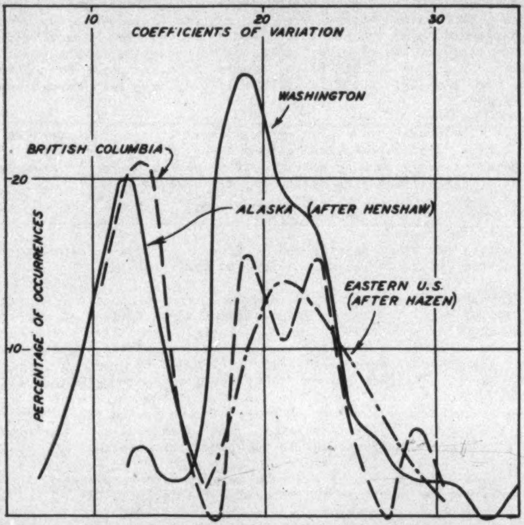

FIG. 1—FREQUENCY OF OCCURENCE OF COEFFICIENTS OF VARIATION

505.6 inches of snow. It is evident that the precipitation in the higher altitudes must exceed 200 inches per year. Quinault has a mean annual runoff of 136.3 inches depth per year, or 10.1 c.f.s. per square mile, from 264 square miles of drainage-area, with the precipitation for 1933 of 169.22, including only 43.1 inches of snow. Paradise Inn in Rainier National Park registered 558.5 inches of snow, which was the greatest depth registered in Washington for 1933. The Chiwawa River draining the east slope of the Cascades had the second largest snowfall for that year, measuring 545.5 inches, or a total precipitation of 90.19, giving a runoff of only 39.0 inches per year, or 2.9 c.f.s. per square mile for a drainage-area of 181 square miles.

This latter figure calls attention to the sudden drop in runoff per square mile in passing from the west side to the east side of the Cascades. Streams heading in the Cascades but flowing down its opposite slopes vary widely in the runoff per square mile, as indicated by Table 2 for streams from contiguous areas.

Table 2--Variation in runoff on adjacent areas in the Cascades

West side of Cascades		East side of Cascades	
River	Yearly runoff	River	Yearly runoff
	inches		inches
Baker	146.5	Chelan	28.9
Sauk	79.8	Chiwawa	39.0
So. Fork of Skykomish	87.9	Wenatchee	50.8

The watersheds in the higher altitudes produce considerably more runoff per square mile than the lower parts of the same watershed, as indicated by the runoff of 50.8 in the Wenatchee at Leavenworth, as against 38.9 at Cashmere. Just how the precipitation or the unit runoff varies with altitude can not be given here, as available data are too meager to give the unit runoff for areas smaller than the drainage areas shown in

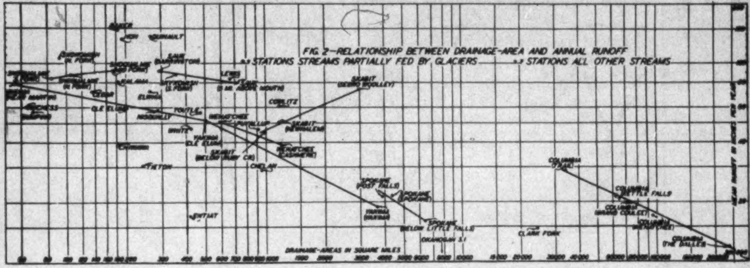

FIG. 2—RELATIONSHIP BETWEEN DRAINAGE-AREA AND ANNUAL RUNOFF

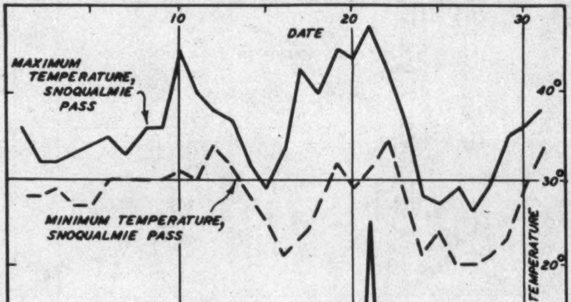

FIG. 3—PRECIPITATION—RUNOFF—TEMPERATURE CURVES, SKYKOMISH RIVER AT GOLD BAR, DECEMBER, 1933

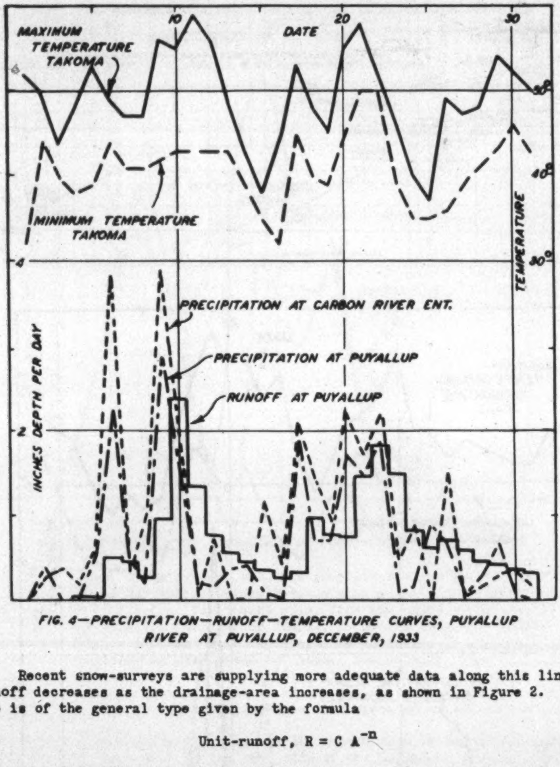

FIG. 4—PRECIPITATION—RUNOFF—TEMPERATURE CURVES, PUYALLUP RIVER AT PUYALLUP, DECEMBER, 1933

Table 1. Recent snow-surveys are supplying more adequate data along this line. The unit-runoff decreases as the drainage-area increases, as shown in Figure 2. The relationship is of the general type given by the formula

$$\text{Unit-runoff, } R = C\ A^{-n}$$

where C varies from 100 for the Yakima River to 3440 for the Columbia and n varies from 0.16 for the former to 0.46 for the latter. The reversed slope of the Skagit River data in Figure 2 arises from the higher unit-runoff of the Baker which enters above the gaging-station at A = 2970.

Another characteristic of snow-fed streams has to do with the excessive rates of flood-flow arising from a pyramiding of storms in which the precipitation of one storm is augmented by the runoff from the melting of snow from an earlier storm. Last December witnessed the severest flood-conditions of record on a number of streams draining the west slope of the Cascades in Washington. It is interesting to note that the floods causing the greatest amount of damage were not necessarily on streams having the highest flood-flow per square mile of drainage-area. The reports of the War Department indicate that the greatest flood-damage was produced by the Puyallup and streams in the vicinity of Centralia. The Puyallup carried a maximum flood of 57,000 c.f.s. or 62.4 c.f.s. per square mile. Table 1 shows a number of streams having a maximum discharge of as much as twice this amount, but which produced much less flood-damage. The actual monetary losses are, of course, affected by many other conditions such as local throttling of the stream-channel by log-jams or bridge-approaches and by excessive tides which prevent the flood-waters from getting away rapidly.

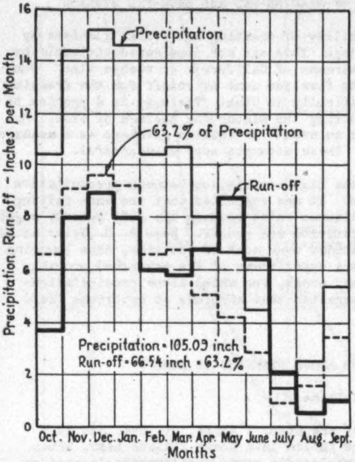

Fig. 5--Relationship of Cedar River run-off to precipitation

It is interesting to note that there were two floods in December which exceeded all recorded floods on certain of the Washington streams. For example, the Puyallup discharged 57,000 c.f.s. on December 10 and 46,000 c.f.s. on December 22, whereas the previous maximum was 40,500 c.f.s. in December 1917. The precipitation was unusually high and almost continuous throughout the State for the month of December. The temperatures were also high during the times of maximum flood, as indicated in Figures 3 and 4. These higher temperatures caused the melting snow to augment the flood-conditions on streams already swollen by rainfall. It is interesting to note the close correlation between temperature, precipitation, and runoff. Temperatures for the higher altitudes of the Puyallup drainage-area were not available so the Skykomish, for which temperatures were at hand, is also given. Note the similarities between the two Figures.

Some have claimed that these floods would have been even greater had there been the usual amount of snow in the mountains. The Weather Bureau reports the average depth of snow on the ground as of December 31 for the years 1933, 1932, 1931, 1930, and 1929, as follows: Western slope of the Cascades, 21.8, 43.7, 53.1, 21.6, 27.3; eastern slope of the Cascades, 28.6, 26.6, 43.4, 10.0, 17.1. The 1933 figure is for the snow remaining after the floods above mentioned and was approximately 66 per cent of normal depth on the western slope and 123 per cent of normal on the eastern slope. I do not believe that a greater amount of snow in the mountains would have increased the flood-flow materially, since there was ample snow still remaining on the ground to have increased the floods had temperature- and rainfall-conditions been such that greater melting would have occurred.

The diurnal flow-variations which are produced by temperature-fluctuations are quite pronounced in streams of this character. As the temperature drops at night the melting of the snow ceases and some of the water running off freezes, so that the stream-discharge is considerably lowered. With the return of the higher daytime temperatures melting again takes place and the discharge is increased. When the streams are at a flood-stage a cold wave may check the flood very quickly and relieve flood-conditions much more rapidly than can occur on streams where floods are produced by rainfall alone. Figure 3 gives the temperature-range for the Skykomish River for the December floods. Freezing temperatures occurred on all but three nights during the month while thawing conditions prevailed during the daytime for most of the month.

In conclusion, I wish to say that the special characteristics of glacier- and snow-fed streams which distinguish them from other streams having about the same total precipitation in the form of rain can best be shown on mass-diagrams or curves showing the storage-requirements for different demands as given in my previous paper (J. Amer. W. W. Assoc., v. 25, p. 94, 1933). The outstanding characteristic of higher summer flow has an important effect on these curves and is illustrated in Figure 5.

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DISCUSSION OF "FLOW-CHARACTERISTICS OF GLACIER-FED AND SNOW-FED STREAMS"

F. C. Scobey inquired about the feasibility of creating artificial glaciers by spreading the streams at the time of freezing. This was not considered advisable by J. E. Church due to the low runoff in the streams of California at such a time. Some of the streams, it was explained, dropped to five per cent of runoff for the freezing period. G. D. Clyde mentioned the same difficulty in Utah. There it is a problem to keep the transport-canals now in use open during the winter due to lack of flow. Mr. Clyde had also had experience with attempts to create artificial glaciers as a means of water-storage by precipitating snowslides. These attempts were unsuccessful.

Question was raised by Dr. Church on the high correlation between precipitation and the runoff of the streams of Washington. It was suggested that the snow falling on impermeable soil, together with the continuous rains keeping the soil primed, might account for the close correlation of precipitation and runoff. Dean R. G. Tyler added that the snow- and runoff-areas remained clouded over most of the time, thus lowering loss from evaporation; furthermore, that the upper areas of the watershed probably received heavier precipitation than the lower areas, for which alone precipitation-measurements were available. Dean Tyler suggested that here was an opportune field for snow-surveying.

RELATIONSHIP OF DEGREE-DAYS ABOVE FREEZING TO RUNOFF

E. H. Collins

The tributary drainage-area (Fig. 1) of the Coeur d'Alene, St. Joe, and St. Maries rivers in northern Idaho supplies the inflow into Coeur d'Alene Lake, which forms the storage-reservoir for several hydroelectric power developments located on the Spokane River.

The entire source of power of the Washington Water Power Company which operates these plants is from hydroelectric power. It was therefore important to obtain some method of predicting water-supply for the approaching low-water period each year.

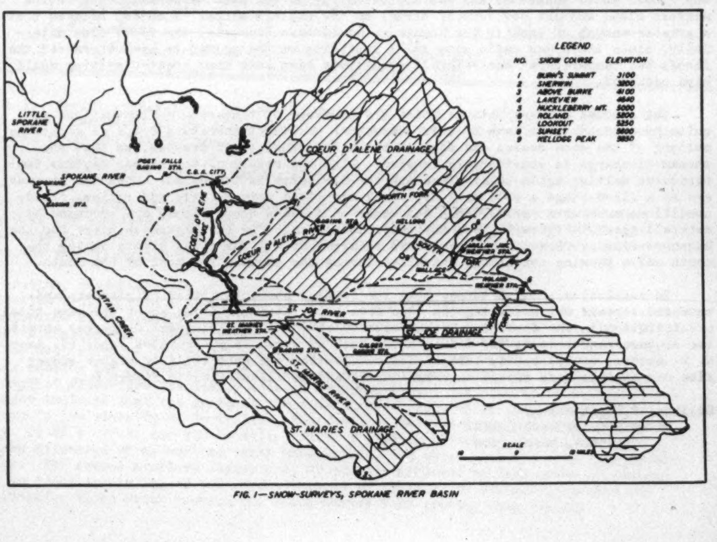
LEGEND
NO. SNOW COURSE ELEVATION
1 BURN'S SUMMIT 3100
2 SHERWIN 3200
3 ABOVE BURKE 4100
4 LAKEVIEW 4640
5 HUCKLEBERRY MT. 5000
6 ROLAND 5200
7 LOOKOUT 5250
8 SUNSET 5600
9 KELLOGG PEAK 5850
LITTLE SPOKANE RIVER
SPOKANE RIVER
SPOKANE
GAGING STA.
POST FALLS GAGING STA.
C. D. A. CITY
COEUR D'ALENE LAKE
COEUR D'ALENE DRAINAGE
NORTH FORK
GAGING STA.
COEUR D'ALENE RIVER
KELLOGG
SOUTH FORK
MULLAN JNC. WEATHER STA.
WALLACE
ROLAND WEATHER STA.
LATAH CREEK
ST. JOE RIVER
ST. MARIES WEATHER STA.
ST. JOE DRAINAGE
CALDER GAGING STA.
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FIG. 1—SNOW-SURVEYS, SPOKANE RIVER BASIN

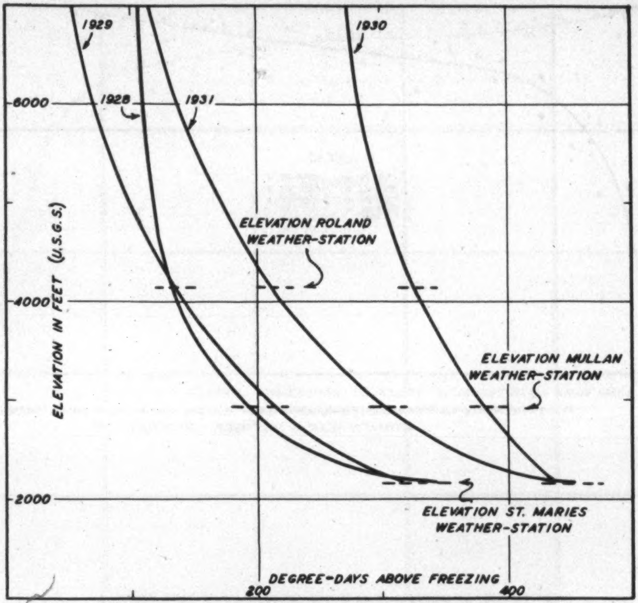

FIG. 2—RELATIONSHIP BETWEEN DEGREE-DAYS ABOVE FREEZING AND ELEVATION, MONTH OF APRIL, 1928-1931

Snow-surveys were attempted. The results, however, were not particularly satisfactory for two reasons. First, the elevation of the drainage-area was not high enough to retain snow after the spring flood. Second, since the storage-rights only allow the retaining of a small percentage of these flood-waters, the water-supply measured as snow only indicated the magnitude of the spring flood which of course is of no value for power.

Further search, therefore, was made for other methods of prediction. It appeared that temperature probably was the major factor in predicting rate of runoff. It seemed also that temperatures below freezing had no effect on runoff. Temperatures above freezing would effect melting of snow, percolation, and evaporation. Attempt was then made to determine a relationship between degree-days above freezing and runoff.

There were available observed temperatures at three stations: (1) Roland in the St. Joe River drainage-area at elevation 4350 feet; (2) Mullan in the Coeur d'Alene River drainage-area at elevation 2980 feet; and (3) St. Maries at the junction of the St. Maries and St. Joe rivers at elevation 2130 feet. The elevation of Coeur d'Alene Lake, the storage-reservoir, is approximately 2130 feet. It was realized that these temperature-data were meager but it was not possible to obtain observers for other stations and no thermographs for long records which could be used without observers were available.

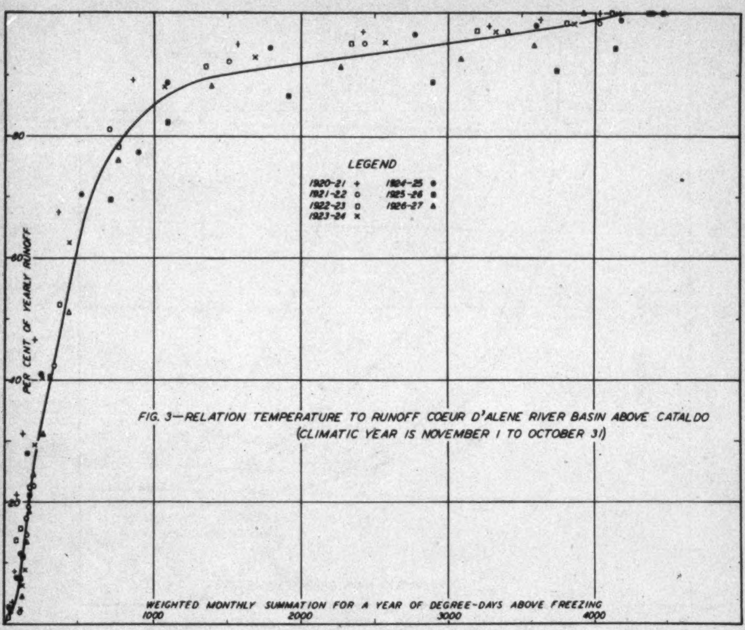

FIG. 3—RELATION TEMPERATURE TO RUNOFF COEUR D'ALENE RIVER BASIN ABOVE CATALDO (CLIMATIC YEAR IS NOVEMBER 1 TO OCTOBER 31)

The first step was to compute the degree-days above freezing at the three stations. These values were then plotted for each month of the year. Figure 2, which is for the month of April, is typical of these curves. Midwinter and midsummer months are of course the least erratic. From these curves degree-days above freezing for other elevations were interpolated.

From a topographic map of the drainage-areas of the three rivers, areas for several elevations were computed. From the combination of these areas and the above degree-days above freezing corresponding to these elevations the weighted mean degree-days above freezing were obtained for each river. A sample of this computation is shown on Table 1.

On each of these three rivers there is a standard United States Geological Survey stream gaging-station. From these stations the monthly mean runoffs of the rivers were obtained.

To establish a prediction-curve the per cent of total annual runoff as measured at these gaging-stations was plotted against the summation of degree-days above freezing. The curves established for the three rivers are shown on Figures 3, 4, and 5. It was found that best results were obtained by starting the year November 1. This was probably due to the fact that freezing temperatures occurred and snow started to accumulate about that time in the higher parts of the drainage-area.

To make a prediction it is necessary to compute the accumulated degree-days above freezing up to date of prediction, say March 1. On the prediction-curve this

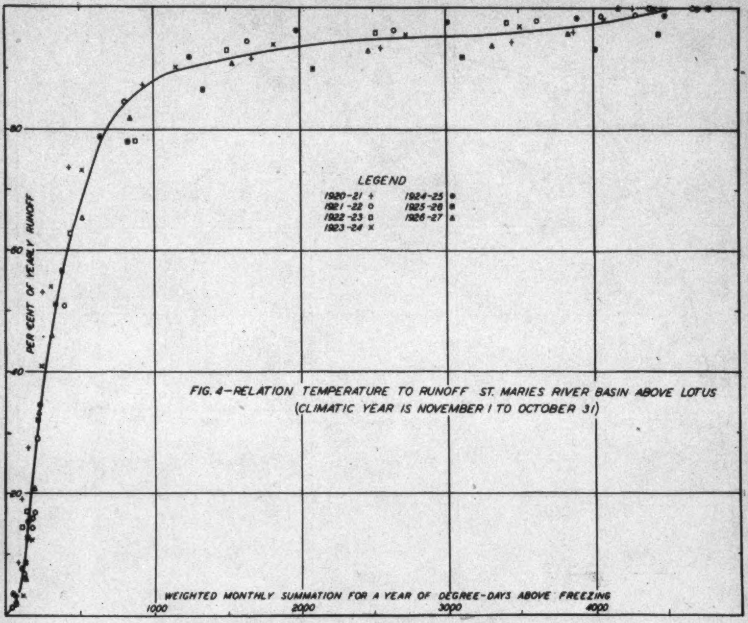

FIG. 4—RELATION TEMPERATURE TO RUNOFF ST. MARIES RIVER BASIN ABOVE LOTUS (CLIMATIC YEAR IS NOVEMBER 1 TO OCTOBER 31)

Table 1--Computation weighted mean degree-days above freezing, Coeur d'Alene River Basin, April 1930

Elevation	Mean elevation	Area	Degree-days above freezing	Area x degree-days
feet	feet	sq. mi.		
2100				
	2550	167	404	67500
3000				
	3500	502	350	175700
4000				
	4500	402	312	124540
5000				
	5500	126	289	36400
6000				
	6400	17	277	4710
6800				
Totals	....	1214	...	408850
Weighted mean degree-days above freezing				336.6

accumulated degree-days above freezing indicates a per cent of the annual water-supply that has occurred. From the stream gaging-stations the actual runoff to March 1 can be determined. From the per cent obtained from the prediction-curve and the actual

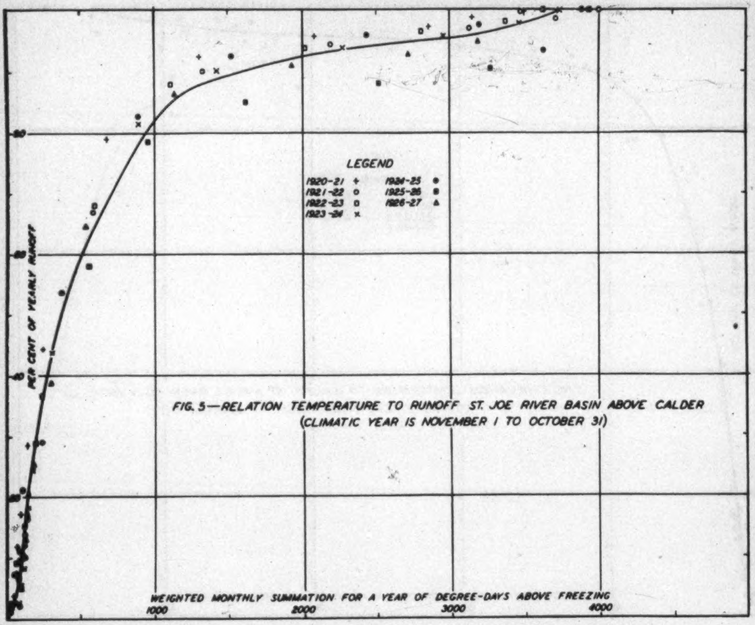

FIG. 5—RELATION TEMPERATURE TO RUNOFF ST. JOE RIVER BASIN ABOVE CALDER (CLIMATIC YEAR IS NOVEMBER 1 TO OCTOBER 31)

flow from the gaging-stations, the total predicted annual water-supply can be computed. The difference between the total predicted and observed to March 1 will then be the predicted remaining supply to be expected. After the spring flood has passed and the plants start to operate on stored water, a prediction of this nature when added to the water-supply in storage gives a measure of total water-supply available for the remainder of the year and its distribution by months may be estimated fairly accurately since the low-water flow does not vary materially in distribution.

Table 2 shows several years of monthly prediction. It will be noted that predictions made from April 1 on appear to be quite consistent and have a fair degree of accuracy.

In conclusion, it is believed that, with a few more observations of temperature at locations chosen with this type of prediction in mind and prediction-curves established by longer records, a fairly definite relationship can be established and valuable predictions accomplished. It has not been necessary to continue this work in recent years owing to the fact that, with above normal water-supply and below normal market for power, predictions were not essential. However, temperature-records and stream-flow records are being collected and can be worked up in the future if desired. It is hoped that when the work is attempted again it will be possible to obtain long-time thermographs so that observations can be obtained even though no observer is available at the desired location.

The development of these data was done by the Engineering Department of the Washington Water Power Company under the direction of V. H. Greisser, Chief Engineer.

Table 2--Predictions of annual runoff in second-foot-days

Month	1926-27		1927-28		1928-29		1929-30		1930-31	
	Forecast	Actual	Forecast	Actual	Forecast	Actual	Forecast	Actual	Forecast	Actual
Dec.	1476500		3745000		884600		441250		383200	
Jan.	1624300		4437000		1150900		430800		622600	
Feb.	1961500		4156000		1500300		501200		540500	
Mar.	2331000		3801000		1694500		651000		680500	
Apr.	2128000		3309000		938100		811600		989700	
May	2092200		2988000		1018400		904150		1111600	
Jun.	2500500		2832000		1058300		975410		1163000	
Jul.	2511500		2764000		1065300		1037500		1140000	
Aug.	2504000		2738000		1071700		1043800		1135500	
Sep.	2496000		2691000		1068800		1038800		1128500	
Oct.	2563600		2649000		1073100		1019900		1114500	
Nov.	2659900	2603181	2633000	2659830	1075400	1066445	....	1049687	....	1131978

Washington Water Power Company,
Spokane, Washington

DISCUSSION OF "THE RELATION OF RUNOFF TO DEGREE-DAYS ABOVE FREEZING"

In the absence of the writer, the paper above was read by the Chairman. Following the reading it was noted that no account of precipitation had been taken into consideration in the paper, but that the forecast of runoff was made entirely on the basis of degree-days above freezing.

The following clarification of the paper has since been made by Carl Elges, J. E. Church, and Emily Richards:

"The novelty of the paper is that the snow-cover is being forecasted in terms of its runoff. As stated by the writer, the forecast in the earlier months of the season is uncertain but becomes more consistent after April 1 when it attains a fair degree of accuracy.

"The reason for the earlier inconsistency lies in the fact that the snow-cover is in the stage of accumulation and settling and does not release its water in harmony with temperature-rise until it has attained the density of "ripeness" or saturation.

"This method naturally is feasible only toward the end of the season when knowledge of the residue of the seasonal flow is chiefly desired. It is possible of application April 1 only in case considerable melting and runoff have already occurred, as in the relatively low watershed of the Coeur d'Alene. In the Central and High Sierra streams little consistency has been found between winter and spring-summer runoff.

"The check of runoff against the forecasts March 1, April 1, May 1, June 1, as summarized in Table 1, indicates the large error usually existing in the March 1 forecast and the increasing accuracy after that date."

Table 1

Water-year	Date	Percentage of forecast to runoff	Percentage-variation	Water-year	Date	Percentage of forecast to runoff	Percentage-variation
1926-27	Mar. 1	89.5	-10.5	1928-29	May 1	95.5	- 4.5
	Apr. 1	81.7	-18.3		June 1	99.2	- 0.8
	May 1	80.4	-19.6	1929-30	Mar. 1	62.0	-38.0
	June 1	96.1	- 3.9		Apr. 1	77.3	-22.7
1927-28	Mar. 1	142.9	+42.9		May 1	86.1	-13.9
	Apr. 1	124.4	+24.4		June 1	92.9	- 7.1
	May 1	112.3	+12.3	1930-31	Mar. 1	60.1	-39.9
	June 1	106.5	+ 6.5		Apr. 1	87.4	-12.6
1928-29	Mar. 1	158.9	+58.9		May 1	98.2	- 1.8
	Apr. 1	88.0	-12.0		June 1	102.7	+ 2.7

IMPROVEMENTS IN FORECASTING THE FLOW OF THE HUMBOLDT RIVER, NEVADA

Carl Elges

Although the Humboldt River, Nevada, termed as the last frontier in stream-forecasting from snow-surveys, has long been the subject of much study and discussion, it still has many perplexing problems that must be solved before forecast accuracy can be obtained. Even when all existing problems have been solved, the forecast will then still be a doubtful one due to the precipitation during the November to July period being equally divided between November to February, the snow-accumulation period, and March to July, the runoff-period. The latter has as much as 30 to 40 per cent effect on the March to July runoff. This factor together with variation in spring and summer temperature, another unpredictable factor, will probably always leave the final Humboldt forecast accuracy to the judgment of the forecaster.

The annual forecast of the stream-flow of the River is of utmost importance to the State Engineer's Office which has the job of distributing the available waters of the stream, and to the agricultural interests on the River. By the forecast, the State Engineer is enabled to set the date of priorities to which water is rightfully available. This in turn warns the farmer not to invest money in crops which he will not have water to irrigate. Consequently, any improvement that can be made in forecasting the flow of the Humboldt is of value to the above agencies and is also a step forward in success of snow-surveying.

During the past few years, the United States Forest Service has developed a group of rangers in the Humboldt Basin who are unsurpassed in reliability as snow-surveyors and can be expected to bring back the desired data taken in a dependable manner. During the past winter, these men have been furnished with complete new sampling-equipment to replace old and worn sets. Consequently, with good men and the best of equipment, all measurements received by the forecaster can be considered reliable.

During the past year, the United States Weather Bureau has established a new cooperative station at a desirable location. This station will prove of considerable value in filling one of the many gaps as soon as a sufficient period of record for the station is available. Unfortunately it is impossible financially for the Weather Bureau to establish additional stations in the Basin where most needed, especially at high altitudes.

One of the greatest handicaps encountered in studying forecast problems on the Humboldt is the lack of stream gaging-stations above diversions. Only during the past two seasons have measurements been taken above diversions on the South Fork and on Lamoille Creek. Since Palisade, the point of gaging for which the forecast is made, is located below approximately one-half of the irrigated lands on the stream and it has been found that owing to diversions and downstream effects the snow-cover versus runoff relationship does not hold, the most important step in obtaining forecast accuracy is to establish gaging-stations above diversions on the tributary streams. Where this is impracticable, smaller basins tributary to the feeders should be selected and used as indicators for each feeder-basin in order that a check can be obtained upon the runoff from the immediate watershed of the snow-fields. Normals for these stations can be computed after several seasons by comparison with precipitation data of nearby weather-stations.

Along with measurements of runoff above diversions, the tributary streams should be gaged at their outlets into the main river-channel so that stream-losses in each basin can be studied. This should be done by the aid of wells to determine the ground-water elevations. A similar study should be made along the main river-channel by dividing it into districts in order to segregate the losses.

With stream-gaging established above diversions to check snow-surveys and to obtain normals to forecast from and with the above study of losses in the tributary streams and in the main river-channel, it is certain that better forecasts will be obtained of the runoff at Palisade or other diversion points after the accumulation of several years of such record.

For the system of forecasting at Palisade, which will necessarily be used until a network of stream-gages is established, it is essential to revise the present normals. For the period 1923 to 1933, the averages in percentages of normal are as follows: Snow-cover, 76; runoff at Palisade, 55; precipitation during runoff, 96. These figures indicate that the normal of runoff at Palisade and the snow-cover normals are not coordinated. Detail figures show that for every year that the runoff is higher than or even approaches the snow-cover percentage, the precipitation during the runoff-period is greatly in excess of normal. It is suggested that the Palisade normal be recomputed in terms of estimated corrected flow. By corrected flow is meant the flow that would have passed Palisade if precipitation during runoff and the soil-conditions on March 1 had been normal.

In order to insure still greater reliability in the snow-courses and to eliminate the possible effects of wind on them, additional courses should be laid out at right-angles to the present ones which now consist of ten to twenty measurements in one straight line.

Also to give more reliable accompanying data, several more precipitation- and temperature-stations would aid considerably toward this end especially if it were possible to have some at high elevations.

A zoning system should be established as soon as topographic maps become available because a large area above the present stream-gage is exposed to low-level snow. This snow is erratic both in occurrence and effect and therefore extreme care must be exercised in evaluating its runoff. This is easily changed by variation in temperature and difference in soil-conditions.

Summarizing, the ultimate ideals sought for the Humboldt Basin are: (1) Forecasting stream-flow above diversions; (2) forecasting probable water available at various points along the stream.

The steps in the attainment of these are the inaugurating or establishing of: (1) Stream-gaging above diversions; (2) stream-gaging at the outlets of tributaries into the main River and at points along the main River so that in conjunction with wells it will be possible to study stream-losses; (3) new normals based on corrected flow; (4) extension of snow-courses so that in each case right-angle courses are measured; (5) several precipitation- and temperature-stations preferably at high elevations; and (6) a zoning system.

Since the inauguration of the above involves considerable expense and the financial ability of the various cooperating agencies is low at present, it will probably be quite a long time before all the items are accomplished. The Nevada Agricultural Experiment Station is leading this project and is cooperating with all agencies to accomplish as much as possible so that forecast accuracy on the Humboldt will be realized in the near future.

Nevada Agricultural Experiment Station,
University of Nevada,
Reno, Nevada

IMPROVEMENTS IN SNOW-SURVEYING APPARATUS

James E. Jones

(Informal discussion)

G. D. Clyde described the Utah improvements on the Mount Rose snow-sampler in which duralumin was used for the tubing, a cheaper bit was constructed, and also a tubular scale. These improvements were made, it was explained, for lightness, cheapness, and facility in packing. J. E. Church added that the Nevada Agricultural Experiment Station was now beginning an experiment with the aluminum tubing.

The bit used by Utah in the samplers drives easily, but does not come out of the snow as easily as the one now used in the Mount Rose design, for it has less cutting power when being drawn out of hard substances.

Professor Clyde mentioned that he had tried to use the springless scale but found it was disburbed too easily. The Utah tubular aluminum-scale has a maximum weighing capacity of somewhat less than 60 ounces or water-inches and, if used with a depth of snow greater than 12 feet, two scales would have to be carried in the field.

In cutting the sampler lengths to three feet, M. R. Lewis found that the Mount Rose dial-scales would not calibrate correctly for the three-foot lengths. There was not enough initial tension to compensate for the lighter tube.

It was pointed out by Professor Clyde that the use of the lighter tubing in constructing the sampler allowed for a shorter tubular scale.

Mr. Lewis stressed the importance of care of scales, and spoke of the screw in the middle of the face becoming loose. It was suggested that this be riveted. Professor Clyde's new scale has a circular indicator on the inner tube, he added. The effect of the wind in weighing was discussed. Dr. Church explained the advisability of shelter-cabins near the snow-courses for the convenience of the field-workers and for added accuracy on the snow-measurements, so that the surveyors could await calmer weather and less sticky snow.

The following letter was received from S. P. Ferguson of Blue Hill Observatory:

> "I think there might be some improvements in snow-measuring apparatus. The light sampler-tube seems to be one, but, it should be made of duraluminum--a heat-treated alloy of aluminum nearly as strong and rigid as cold-rolled steel of which the tubes are made at present. We have used this material instead of brass for many instruments with excellent results; the only defect of importance is that it, like aluminum, can not be soldered easily and fittings have to be riveted or screwed together.
>
> "Ordinarily, about three grades--soft, heat-treated, and hard--can be had, in rods, tubes, and sheets; the heat-treated grade is best for most purposes though for sampling-tubes and scales, where durability is desired, the hard might be best. It costs the same as aluminum.
>
> "Time has not permitted experimenting with a new spring-balance, but it has occurred to me that a simple, straight tubular scale set to register zero when supporting the empty tube, might be better than the expensive dial-scale we now have. The advantages would be that estimates to fractions of an inch or cm of water would be accurate, it probably would be more rugged or durable and somewhat lighter than the dial-scale, and much less costly to make. The disadvantage is its great length--it might have to be nearly two feet long to provide a scale reading by estimate to 0.1 inch of water. The usual adjustments can be provided.
>
> "I am not familiar with springless scales but my notion is that they are better for a fixed station than for field-service."

MINUTES AND RESOLUTIONS PASSED BY THE WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

The Conference met in close affiliation with the Section of Hydrology of the American Geophysical Union. Approximately 44 were in attendance. The scheduled meeting of the Conference was held under the chairmanship of Harlowe M. Stafford on Thursday afternoon, June 21, at 2:00 p.m. in Room 104, Engineering Building, University of California, at Berkeley. George D. Clyde and Emily Richards acted as secretaries.

J. C. Stevens of Portland, Oregon, who had been expected to speak on "The Stevens annual snow- and rain-recorder," was unable to attend. He sent the following brief description and comment:

> "The Stevens snow- and rain-recorder (see Fig. 1) operates on the principle of weighing the precipitation. A collector is mounted on top of the housing which communicates with a storage-tank supported on a weighing-beam. One end of the beam is supported by an accurate spiral spring. As the tank becomes loaded the spring extends and the movement of the beam is magnified and recorded on a strip chart in terms of inches of precipitation by a Stevens Type A30 water-level recorder. The entire mechanism is contained within a weather-proof metal

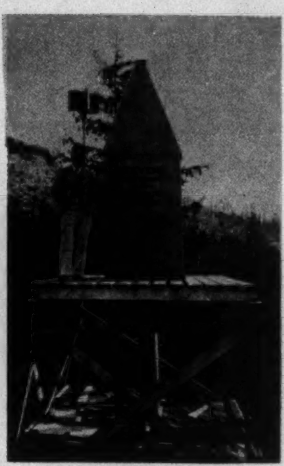
Fig. 1

housing mounted on a platform so as to be always above the deepest snow-drift. The weight driving the recorder-clock and the counterweight move in a metal pipe extending downward from the base of the housing of which it is a sealed part.

"The recorder, designed primarily for isolated localities, will run ten months or longer with one setting. The tank-capacity is sufficient to hold upwards of 100 inches of precipitation passing through the collector.

"The recorder can be put in operation in the fall of the year, the graph of accumulated precipitation in inches being removed in the following spring.

"To insure uniform deposition of snow in the tank during high winds, a wind-motor is attached to the housing and serves to slowly turn the storage-tank when snowfall is accompanied by heavy winds. This also prevents the snow from building up on one side of the collector.

"The recorder, the culmination of several years' experimentation, is manufactured and distributed by Leupold, Volpel, and Company, Portland, Oregon."

The following Executive Committee was chosen for 1934-35: J. E. Church, Meteorologist, Agricultural Experiment Station, Reno, Nevada; George D. Clyde, Professor of Irrigation and Drainage, Utah Agricultural Experiment Station, Logan, Utah; James E. Jones (Chairman), City of Los Angeles Department of Water and Power, Los Angeles, California; Joseph Kittredge, Jr., Professor of Forestry, University of California, Berkeley, California; Harlowe M. Stafford, Hydraulic Engineer, Division of Water Resources, Sacramento, California.

A greater intimacy and interchange of views will be sought through a questionnaire to all workers in the field of snow-surveying. The solution of present problems will be hastened. Snow-surveying as an essential feature of snow-hydrology will be stressed. The Conference will be maintained.

The Conference adopted three resolutions, namely:

(1) Of deep appreciation to Mr. Scobey, Professor O'Brien, Professor Woods, and Secretary Nauta for aiding the affiliation between the western meeting of the American Geophysical Union and the Western Interstate Snow-Survey Conference, and to the University of California for courtesies as host.

(2) Of gratitude to Director Doten of the Nevada Agricultural Experiment Station for publication of proceedings of the Conference in 1933 and to Mr. Scofield for inclusion of proceedings of the present meeting in the Transactions of the Section of Hydrology of the American Geophysical Union.

(3) Of high esteem to Dr. J. E. Church for pioneering in the field of snow-surveying.